THE INFLUENCE OF CONFORMATION AND GAIT OF THE HIND LIMB ON THE AETIOLOGY OF CRANIAL CRUCIATE LIGAMENT RUPTURE IN ROTTWEILERS AND RACING GREYHOUNDS

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I declare that the contents of this thesis are my own work and have not been presented to any university other than the University of Edinburgh

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To my family, friends and colleagues for all their help and support.

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ABSTRACT

The thesis investigates the hypothesis that the conformation and gait of the hind limb of certain large breeds of dog predisposes to rupture of the cranial cruciate ligament. It is divided into three parts.

The first part studies the breed incidence of cranial cruciate ligament rupture in dogs. The second compares the gait and conformation of the hind limb, with particular attention to the stifle joint, in two large breeds of dog, the Rottweiler, in which cruciate damage is common, and the Racing Greyhound, in which it is rare. The third part compares the biomechanical properties of the cranial cruciate ligament and osseous geometry of the tibial plateau in the two breeds.

A survey of 72 general practices and 4 veterinary school case records showed a high incidence of cranial cruciate ligament rupture in the Rottweiler relative to its popularity in the general dog population and a lower mean age at the onset of clinical signs compared to all the other breeds affected. Cruciate ligament damage was rarely reported in the Racing Greyhound.

Conformation and kinematic gait analysis of 28 Rottweilers and 28 Racing Greyhounds was done with a high speed cinecamera, recording at 50 frames per second, and a microcomputer-based gait analysis system. Frame by frame analysis of the cinefilm showed that the hind limb joints of the Rottweiler exhibited statistically significantly greater ranges of angular motion during the walk and trot compared to the Racing Greyhound. The stifle joint was more extended in the Rottweiler at the

commencement of weight-bearing and the stride length was greater, which together, lead to a tendency to overextend the stifle joint stressing the cranial cruciate ligament.

Biomechanical testing of cadaver stifles in 13 Rottweilers and 15 Racing Greyhounds, at the flexion angles determined from the gait analysis, examined the stability of the joints and the material and structural properties of the cranial cruciate ligaments and their bony attachments when loaded in tension. The geometry of the tibial plateau was also investigated. The stifle joints became less stable with increasing joint flexion, the Rottweiler joint being consistently more lax than the Racing Greyhound. This may explain the tendency of the Rottweiler stifle joint to extend more fully than the Racing Greyhound, which is recognised as one mechanism of cranial cruciate ligament rupture. In extension, the tensile strength of the Racing Greyhound cranial cruciate ligament was statistically significantly greater than the Rottweiler, although the strength of the latter increased with increasing joint flexion. The contact angle between the femoral condyles and the tibial plateau changed as the joint was flexed, more so in the Rottweiler where there was a greater backward slope of the plateau.

The conformation and gait of the Rottweiler hind limb does influence cranial cruciate ligament damage. The normal Rottweiler stifle joint is more extended than the Racing Greyhound at foot placement when the cranial cruciate ligament is weaker. As the joint flexes, the ligament is stronger but the greater backward slope of the tibial plateau contact point results in a greater force tending to move the tibia forward relative to the femur which must be counteracted by the cranial cruciate ligament. Therefore as the Rottweiler stifle joint flexes from full extension, the ligament and its attachments become biomechanically stronger but the load on the cranial cruciate ligament becomes greater.

INTRODUCTION

" The extent to which the stifle joint of a specific animal is cranial cruciate ligament-dependent is directly related to the anatomical orientation of the joint, kinematics of the joint and the gait pattern of the individual animal"

Arnoczky S.P. 1990

One of the most common causes of chronic hind limb lameness and osteoarthritis in the dog is complete or partial rupture of the cranial cruciate ligament in the stifle joint.

Despite numerous studies, there is no method of repair which consistently leads to a completely satisfactory return to normal joint function. Therefore prevention must be better than cure.

A number of factors have been suggested which may predispose to damage of the cranial cruciate ligament, these include gait and conformation of the hind limb (Vasseur et al 1985, Arnoczky 1990, Robins 1990) although there is no data available on whether conformation is related to this disease and there has been very little work done comparing the gaits of different breeds of dog despite their obvious diversity.

Anecdotally, some breeds are reported to be more prone to rupture of the cranial cruciate ligament than others, and recent observations indicate that the condition, presenting as chronic lameness of gradual onset rather than acute, is seen more frequently in younger dogs of the larger breeds (Denny and Barr 1987, Bennett et al 1988).

The aim of this study was to compare the gaits of two breeds of dog, examining the relationship between the straightness of the stifle joint and the incidence of cranial cruciate ligament rupture, to test the hypothesis that the conformation and gait of the hind limb of certain large breeds of dog predisposes to rupture of the cranial cruciate ligament. This involved examining the conformation and gait of the dogs and biomechanically testing cadaver stifle joints, of the chosen breeds, to establish the relationship between joint angulation and failure of the cranial cruciate ligament.

The breeds chosen were the Rottweiler which visually exhibits a straight stifle joint and where cranial cruciate ligament rupture is common, and the Racing Greyhound which has a 'good' conformation and rarely presents with cranial cruciate ligament rupture.

No experimental animals were used in this study. The dogs used for the kinematic analysis of gait belonged to members of the public.

The gait analysis data in this study was collected from live, healthy dogs under field conditions, which are more difficult to standardise than the relatively controlled environment of the laboratory. However, the standardisation of the recording techniques and the large sample size used, should lead to standardised results with errors reduced to a minimum.

This study involves:

1. Examining the breed incidence of cranial cruciate ligament rupture in the dog population of the United Kingdom.

2. Studying the conformation and the kinematic walking and trotting gaits of Rottweilers and Racing Greyhounds. The angular movements of the stifle joint during locomotion were particularly noted.

3. Studying the biomechanical properties of the stifle joint and the osseous geometry of the tibial plateau at particular joint angles determined from the gait analysis.

DATA ANALYSIS

Two methods were used to determine if the data results were Normally distributed.

The individual data (where sample size N > 10) were plotted and found to exhibit Normal (Gaussian) distributions.

Also the median points were determined and found to closely match the mean values calculated for each set of data, a good indication of Normal distribution.

The data were found to be Normally distributed and as such were analysed using mean, standard deviation, standard error of the means and t-tests (where N >4).

In the mathematical analysis of the results in this study, where the sample size (N) is less than 4, no standard deviation, standard error of the means or t-test statistical analyses were carried out. However, the trends in the figures are discussed.

CHAPTER ONE

ANATOMY AND FUNCTION OF THE CANINE STIFLE JOINT

" For a large number of problems there will be some animal of choice, or a few such animals in which it can be most conveniently studied"

August Krogh Principle 1929

1.1 EVOLUTION

The stifle joints exhibited in today's living tetrapod population are the result of nearly 400 million years of evolution. The common ancestry of all living mammals, reptiles and birds can probably be traced back to the amphibian *ERYOPS* of the Carboniferous period (320 million years ago), although there is evidence of earlier osseous weight-bearing appendages in the *ICHTHYOSTEGA* amphibian 370 million years ago (Javik 1981). This common evolutionary route explains the similarity in the appearance and functional dynamics of the stifle of many diverse species, frog, alligator (which has three cruciate ligaments), sheep, chicken, dog, human.

Even 320 million years ago the stifle joint was a complex structure comprising cruciate ligaments, menisci, bicondylar femurs and collateral ligaments (Haines 1942). During the Mesozoic period (around 180 million years ago) the apex of the femur rotated cranially to bring the limb nearer to the midline allowing for more efficient locomotion (Dye 1988) and producing the appearance seen in extant mammals and birds today. At the end of this period the patella bone also evolved.

Dye (1988) classified the mammalian stifle joint into 3 categories:- **Unguligrade.** e.g. horse, pig, cow, which lack full stifle extension and are loaded in flexion.

Plantigrade. e.g. human whose stifle is loaded in full extension. Humans are the only known species which are plantigrade and also functionally bipedal. **Digitigrade.** e.g. carnivores. They can nearly extend the stifle joint fully but it is loaded in flexion.

Despite their common ancestry, the species differences in stifle anatomy and functional dynamics stated above and in later sections mean that care is needed when interpreting and extrapolating data from animal models. There is no single animal model which matches the anatomy and biomechanics of the dog stifle joint as there are subtle differences between species (Arnoczky1990)

1.2 ANATOMY OF THE STIFLE JOINT

The canine stifle joint is classified as a diarthrodial, condylar joint and is arguably the most complex in the body (Haut and Little 1969, Arnoczky 1985). It has also been classified as a spiral joint because the joint axes and collateral ligament attachments are eccentric (Nickel 1986). The joint exhibits two main types of motion, extension and flexion which predominate during weight-bearing and axial rotation seen mainly during flexion without weight-bearing (Rudy 1974a). It is a link between the two main bones of the pelvic limb, femur and tibia. There are, in fact, three osseous articulations within the stifle joint; femoropatellar, proximal tibiofibular and femorotibial, the latter being the most important in hindlimb function (Adams 1986). The main anatomical features of a diarthrodial joint are; ligaments, fibrous capsule, synovial membrane, articular cavity, articular cartilage, muscles, tendons, blood vessels, nerves and periosteum (Bennett 1991).

1.2.1 OSSEOUS ANATOMY

1.2.1.1. FEMUR (Fig. 1.1 and 1. 2).

The femur is the heaviest and largest bone in the body (Nickel et al 1986) and in a well proportioned breed it is slightly shorter than the tibia (Evans 1993a). The distal end has caudally projecting medial and lateral condyles covered with articular cartilage and separated by an intercondylar fossa from which the cruciate ligaments originate (Adams 1986). Both condyles articulate directly with the tibia to some extent but mainly with the intra-articular menisci. In the sagittal and transverse planes the lateral condyle is convex, the medial is smaller and less convex. The femoral trochlea is a wide articular groove which is continuous with the articular surfaces of the femoral condyles and articulates with the patella. The medial trochlear ridge, which limits the femoral trochlea medially, is slightly thicker than the lateral (Evans 1993a). The main blood supply to the distal femur is the superior genicular artery which provides the intraosseus arteries entering the femoral condyles caudally (Tirgari 1978a).

1.2.1.2. TIBIA (Fig. 1. 3 and 1.4).

The proximal tibia is triangular and has a plateau which comprises articular and non-articular areas. The medial tibial condyle (medial articular area) is oval-shaped, the lateral is circular and they are convex sagittally and concave transversely. The lateral condyle is larger than the medial. The condyles are divided by a sagittal non-articular strip and an intercondylar eminence and the lateral condylar area is where the cranial meniscus and cranial cruciate ligament (CrCL) attach (Evans 1993a). The caudal tibial plateau slopes inferiorly (caudal and distal), the lateral side slightly more than the medial (Dye 1988). Therefore there is a tendency for the femur to move caudally, relative to the tibia, when weight-bearing. This movement is primarily checked by the intact cranial cruciate ligament (Arnoczky 1990). The tibial tuberosity is a proximocranial process where the quadriceps femoris and parts of the biceps femoris and sartorius insert (Adams 1986, Evans 1993a). The main blood supply to the proximal tibia is from the recurrent branches of the cranial tibial artery and the main popliteal artery (Tirgari 1978a).

The medial-lateral femoral and tibial asymmetries described are important when the movement of the stifle joint is considered later in the chapter.

The articulating surfaces of the femur and tibia are covered with hyaline cartilage which varies in thickness. It is thickest in the young and in joints which transmit large forces during weight-bearing (Evans 1993a). The cartilage is important in joint lubrication and there is only a small area of contact between the articulating surfaces at any one time. When this area of cartilage is heavily loaded (squeezed) during weight-bearing, a glycoprotein-lubricating fraction is extruded and results in hydrostatic lubrication (squeeze-film) between the articular surfaces and reduces the coefficient of friction between them (McIlwraith 1982, Beale and Goring 1993). Because the contact area changes as the joint moves, no area is badly 'squeezed out' (Alexander 1968). During low load bearing, boundary lubrication (as opposed to hydrostatic) is operative which relies on hyaluronate acting as the lubricant of the synovial membrane (McIlwraith 1982).

1.2.1.3. SESAMOID BONES

PATELLA (Fig. 1.1). This is the largest sesamoid bone in the body, oval shaped and curved to articulate with the trochlea of the femur. The distally located apex is more pointed than the base. Embedded in the tendon of the quadriceps femoris muscle, which are stifle joint extensors, it protects and alters the direction of pull of the tendon, increasing the mechanical advantage of the quadriceps muscle group (Adams 1986, Evans 1993a, Vasseur 1993). Either side of the patella are parapatellar fibrocartilages which articulate with the femoral trochlear ridges and from these, rudimentary ligaments or retinaculae, originate which help prevent medial-lateral subluxation of the patella from the femoral trochlear groove. The patellar blood supply is a circumferential plexus from the descending genicular and superior pole arteries with an intraosseus network (Tirgari 1978a).

FABELLAE. (Fig. 1.2 and 1.4). There are two fabellae in the heads of the gastocnemius muscle which articulate with the proximocaudal surfaces of medial and lateral femoral condyles. A third fabella is in the popliteal muscle tendon and articulates with the lateral tibial condyle (Evans 1993a).

1.2.1.4. FIBULA

The fibula is a long thin bone whose head articulates with the caudolateral part of the lateral tibial condyle. It is mainly for muscle attachments and supports little weight (Evans 1993a).

1.2.2 SOFT TISSUE ANATOMY

The normal stifle joint is stabilised by muscles, tendons and ligaments (Henderson and Milton 1978) as well as by the joint capsule, menisci and joint geometry.

1.2.2.1 MUSCLE

The stifle joint is stabilised by three muscle groups, hamstring, quadriceps and gastrocnemius. Muscles that orginate or insert near the stifle joint tend to stabilise it, those with attachments further away tend to move it. Muscles located mainly on the caudal thigh tending to extend the hip and flex or extend the stifle depending on the position of the limb include; biceps femoris, gracilis and semimembranosus (hamstrings), and the caudal belly of the sartorius muscle (Fig. 1.5). Their actions stabilise the joint and support the CrCL function by providing a caudal traction force on the tibia relative to the femur (Henderson and Milton 1978). The long digital extensor tendon, which originates between the lateral femoral condyle and the lateral trochlear ridge, crosses the joint craniolaterally and gives minor cranial joint support. The quadriceps group, comprising the rectus femoris muscle and the medial, lateral and intermediate vastus muscles, act as joint stabilisers and extensors inserting together on the tibial tuberosity via the straight patellar tendon (Fig. 1.6) (Dyce et al 1952, Nickel et al 1986). When contracting, they apply cranioproximal traction to the tibia via the straight patellar ligament whilst the patella transfers weight loading caudally to the femoral trochlear resulting in forces of opposing directions acting on the distal femur and proximal tibia and an extension moment about the joint. The cranial proximal tibial traction and the caudal femoral pressure act as biomechanical antagonists to the CrCL. The gastrocnemius muscle is also antagonistic to CrCL function. Originating on the medial and lateral supracondylar tuberosities on the distal caudal femur it runs distally to insert via the common calcanean tendon on the tuber calcis (Fig. 1.6). During the propulsive phase of weight-bearing the gastrocnemius muscle contracts to help stabilise the stifle joint resulting in a large caudodistal force acting on the femur tending to slide the femur caudally relative to the tibia which adds to the effect of the quadriceps group. Following cranial cruciate ligament rupture, dogs will often hyperextend the hock to relax the gastrocnemius muscle, reduce the caudodistal distraction force and thus passively 'stabilise' the joint (Henderson and Milton 1978). The effect of the gastrocnemius muscle on CrCL tension is the basis of the tibial compression test for ligament rupture and will be discussed in chapter 2. The femoral attachment of the popliteal muscle tendon is in the popliteal fossa on the lateral femoral condyle caudal to the long digital extensor origin and runs caudally beneath the lateral collateral ligament. It primarily acts to rotate the tibia inwards during joint flexion as well as assisting in that flexion (Rudy 1974a).

1.2.2.2. INFRAPATELLAR FAT PAD

This is found in the triangular space between the straight patellar ligament, distal femur and the proximal tibia, and it thickens distally (Fig. 1.7) (Evans 1993b). The fat pad separates the fibrous and synovial portions of the joint capsule distal to the patella (Evans 1993b). Its blood supply comes from the inferior medial genicular artery which supplies the cranial fat pad, which in turn contributes to the distal cranial cruciate ligament blood supply. The fat pad contribution is more significant in the dog than in man (Amiel et al 1990a).

1.2.2.3. JOINT CAPSULE

The stifle synovial joint capsule is the largest in the body and consists of three intercommunicating sacs (Evans 1993b). Two sacs are between the medial and lateral femoral and tibial condyles and the third is the patellar pouch which extends laterally from the parapatellar fibrocartilages to the femur, attaching approximately 2cm from the trochlear ridges. Proximally the femoropatellar synovial capsule extends 1.5cm from the patella under the quadriceps femoris tendon (Payne and Constantinescu 1993). The infrapatellar fat pad separates the joint capsule distally. Often there is a small synovial bursa between the straight patellar ligament and the tibial tuberosity (Evans 1993b).

1.2.2.4. MENISCI

Medial and lateral menisci are located between the femur and tibia (Fig. 1.7). They are fibrocartilagenous and composed of dense fibrous tissue, mainly collagen plus elastic fibres with occasional chondrocytes (Bennett and May 1991a). Semilunar in shape, they are concave, wedge-shape in cross section with the thinner side axially (Arnoczky and Marshall 1981, Payne and Constantinescu 1993). Synovial fluid provides the majority of the meniscal nutrition although the peripheral (abaxial) 10-15% gets its blood and nerve supply from the synovial membrane (Constantinescu and Cosoroaba 1973, Bennett and May 1991a) via branches of the inferior genicular artery amongst others (Tirgari 1978a). The axial portions are avascular. Some authors report that the lateral meniscus is slightly thicker and forms a greater arc than the medial (Evans 1993b), others that the lateral meniscus is longer and narrower (Dyce et al 1952). Six ligaments hold the menisci in position (Fig. 1.8); craniomedial and craniolateral meniscotibial ligaments (attach their respective menisci to the intercondylar area), caudomedial and caudolateral meniscotibial ligaments (attach the medial meniscus to the intercondylar area, and the lateral to the popliteal notch), cranial intermeniscal ligament and the lateral meniscofemoral ligament (Fig. 1.8) which runs from the caudal lateral meniscus to the medial femoral condyle facing the femoral intercondylar fossa and is the only meniscal attachment to the femur (Hohn and Newton 1975, Nickel et al 1986, Evans 1993b) (equivalent to the human ligament of Humphrey - Girgis et al 1975). Hohn and Newton (1975) reported the frequent presence of a very small medial meniscofemoral ligament running from the caudal medial meniscus to join the ascending caudal cruciate ligament, however there are no other references to this structure and Arnoczky and Marshall (1977) reported that there is no attachment between the caudal cruciate ligament and the menisci. Both menisci are firmly attached to the joint capsule and the medial meniscus is also attached to the medial collateral ligament (Hohn and Newton 1975, Payne and Constantinescu 1993). Many functions of the menisci have been proposed:-

a) To transmit weight across the joint. (Hulse and Shires 1985 suggested up to 65%, Goodfellow and O'Connor 1980 - 50%).

b) To absorb compressive forces (shock absorption) and so protect the articular cartilage (Cox et al 1975, Arnoczky and Marshall 1981, Bennett 1991, Payne and Constantinescu 1993).

c) To maintain craniocaudal and rotatory stability by improving joint congruity and deepening the articular surfaces of the tibial plateau (Arnoczky and Marshall 1981, Bennett 1991). If two surfaces of compliant material are to match one another under load then the surfaces will seem incongruous when not loaded and will conform when loaded. Menisci act as washers for the transition from hinge to rotation motion (Radin and Bryan 1970).

d) To increase joint lubrication efficiency by producing a hydrodynamic wedge of synovial fluid (MacConaill 1931, Le Gros Clark 1965). This complements the hydrostatic (and boundary) lubrication mechanisms between articular surfaces which were described earlier (1.2.1.2.).

e) To prevent impingement of synovial membrane and capsule (Constantinescu and Cosoroaba 1973, Cox et al 1975).

f) To protect joint margins (Bennett 1991).

g) The nerve supply may have sensory functions enabling precise fast response to changes of pressure in the joint and fine control of complex movements (Le Gros Clark 1965).

The menisci do not cover all of the tibial articular cartilage in the standing position (Dyce et al 1952) and as the joint extends the menisci move forward on the tibial plateau. Their cranial progression is halted when they wedge between the femoral trochlea and the tibial condyles, and by the tensioning of the caudal cruciate and meniscofemoral ligaments (Dyce et al 1952). In flexion the menisci glide caudally and the lateral meniscus may protrude over the caudal edge of the tibial plateau (de Lahunta and Habel 1986).

1.2.2.5. COLLATERAL LIGAMENTS

The collateral ligaments are medial and lateral thickenings of the fibrous membrane of the joint capsule (Evans 1993b). **The medial collateral ligament** (Fig. 1.7) is composed of two parts. Both parts originate on the medial femoral epicondyle (centre of joint rotation), the deep shorter portion attaches to the medial meniscus and joint capsule and is tense in extension and relaxed in flexion. The longer, superficial portion inserts on the medial tibia and remains taut in flexion and extension. Therefore some part of the ligament is taut throughout joint motion but is most taut in extension (Rudy 1974a). Where it passes over the tibial condyle there is a bursa (Evans 1993b). The ligament mainly prevents valgus although it also constrains rotation to a lesser degree (Vasseur and Arnoczky 1981, Payne and Constantinescu 1993). **The lateral collateral ligament** runs from the lateral femoral condyle to the head of the fibula, lateral to the popliteal muscle tendon (Fig. 1.7). It has no attachments to the lateral meniscus. It stabilises the lateral joint, resisting varus stress together with the lateral joint capsule, popliteal tendon and cruciate ligaments (Vasseur and Arnoczky 1981, Arnoczky 1990). The lateral collateral ligament is taut in extension and is responsible for the 'screw-home mechanism' which is present to a minor degree in dogs compared to humans (see 1.3). During stifle flexion the lateral collateral ligament slackens and the tibia can rotate internally on the femur. During extension the lateral collateral ligament becomes taut and the tibia externally rotates (Hulse and Shires 1985).

1.2.2.6. CRUCIATE LIGAMENTS.

The cruciate ligaments were first described in man by Claudius Galen in 250AD

STRUCTURE

GROSS ANATOMY. The two cruciate ligaments, so named because they cross in the joint (Haut and Little 1969), are probably unique because of their location, stresses and lack of soft tissue support and blood supply (Frank et al 1985), and are believed to be essentially the same in the dog as in man (Arnoczky and Marshall 1977, Arnoczky 1990). They are intra-articular but extra-synovial, i.e. they are covered by synovial membrane (Arnoczky and Marshall 1981, Adams 1986) and have the same embryological origin as the menisci (Segal and Jacob 1983).

A detailed description of the gross anatomy of the cruciate ligaments has been written by Arnoczky and Marshall (1977) (Fig. 1.7, 1.9, 1.10, 1.11).

Cranial cruciate ligament (CrCL). Proximally it originates on a fossa on the caudomedial part of the lateral femoral condyle, caudal to the caudal border of the femoral shaft (Heffron and Campbell 1978). Some of the fibres making up the craniodorsal edge of the CrCL originate from the caudolateral intercondylar area. The attachment is shaped like a segment of a circle with its long axis vertical (Fig. 1.9). The ligament runs cranially, medially and distally, passing beneath the intermeniscal ligament (Arnoczky 1990), to end on the cranial intercondylar area of the tibia. The tibial insertion is comma-shaped with a horizontal axis (Fig. 1.11) and is between the attachments of the craniomedial meniscotibial ligament caudally and the craniolateral meniscotibial ligament cranially (Heffron and Campbell 1978). Some fibres insert on the craniolateral side of the medial intercondylar tubercle. The ligament rests against the lateral tibial eminence and the cranial horn of the lateral meniscus. There is no attachment between the CrCL and the menisci (Fig. 1.7) (in man there is a slip of the attachment to the lateral meniscus Girgis et al 1975). The ligament spirals about 90 degrees between its proximal and distal attachments and as the joint flexes, the ligament twists more. The ligament is not a simple band in constant tension (Amis and Dawkins 1991), and is divided functionally into two portions which can be appreciated when viewed from cranially (Heffron and Campbell 1978, Clark and Sidles 1990). The larger caudolateral part is taut in extension and loose in flexion, the smaller craniomedial part is taut in flexion and extension (Fig. 1.12, 1.13, 1.14) (Brantigan and Voschell 1941, Girgis et al 1975). As the joint flexes, the vertical femoral origin becomes horizontal, the origin of the caudolateral part of the CrCL moves closer to the tibial insertion and so becomes looser (Fig. 1.14). Because the distance between the origin and insertion of the craniomedial portion varies little during flexion and extension resulting in a fairly constant degree of tautness, it is the primary check against cranial translation of the tibia relative to the femur (cranial drawer), the caudolateral part is secondary (Arnoczky and Marshall 1977, in man - Furman et al 1976).

The caudal cruciate ligament originates from the ventral area of the lateral side of the medial femoral condyle. The origin is elliptical with a horizontal long axis and its most cranial part reaches the articular cartilage of the femoral trochlea (Fig. 1.10) (Arnoczky and Marshall 1977). In 63% (19 of 30) of dogs examined by Arnoczky and Marshall (1977) the femoral origin of the caudal cruciate ligament contains some fibres from the lateral meniscofemoral ligament. The caudal cruciate ligament runs medial to the CrCL to insert on the medial popliteal notch of the tibia (Fig. 1.11). Most authors have reported no attachment between the caudal cruciate ligament and the menisci (Arnoczky and Marshall 1977, Evans 1993b) but a very small medial meniscofemoral ligament running from the caudal medial meniscus to join the ascending caudal cruciate ligament has been described (Hohn and Newton 1975). As with the CrCL, the caudal cruciate ligament also twists as the joint flexes, its fibres spiralling in the opposite direction, but not to the same degree (Rudy 1974a). The caudal cruciate ligament has two bands which are less distinct than in the CrCL. The cranial band is taut in flexion, loose in extension, the reverse is seen in the caudal band. As the joint flexes, the horizontal, femoral, caudal cruciate ligament origin becomes vertical, the origin of the cranial part moves further from the tibia and so becomes taut. The reverse is true for the caudal part (Fig. 1.15). The length of the cruciate ligaments quoted in the literature varies considerably which reflects not only the technical difficulties in measuring the length, but also deciding exactly which fibres to measure and whether to include the areas of insertion (CrCL lengths; 8.1mm - Gupta et al 1971, 18.6mm - Vasseur et al 1985, 20.6mm - Johnson et al 1989). However it is generally agreed that the ratio of the CrCL to caudal cruciate ligament is approximately 1:1 with the caudal cruciate ligament being slightly longer.

MICRO-ANATOMY

The morphology, physiology and biochemistry of ligaments are comparable across the species. Ligaments are dense, regularly orientated connective tissue made up of fibroblasts in an extracellular matrix of collagen (mainly type 1), proteoglycan and water (Arnoczky 1990) (Fig. 1.16).

The CrCL is composed of tightly apposed collagen subfascicles, 20μm diameter (Clark and Sidles 1990), surrounded by endoligamentous tissue, endotenon, where blood vessels, fat cells and elastin are localised (Yahia and Drouin 1989). 1 to 10 subfascicles are grouped into fascicles of differing cross-sectional shapes, 20 to 400 μm diameter with a mean cross sectional area of $250.10^{-3}mm^2$ (Yahia and Drouin 1989). The fascicular widths vary least in canines compared to man and rabbits (Clark and Sidles 1990). The fascicles are separated from each other by loose connective tissue, epitenon (Danylchuk et al 1978, Arnoczky et al 1982, equivalent to the endoligamentous tissue quoted by Alm and Stromberg 1974), which is continuous with the endotenon and originates from the paraligamentous membrane (paratenon) which surrounds the whole ligament (Alm and Stromberg 1974, Yahia and Drouin 1989). The paraligamentous membrane is made up of one to several layers of synovial cells and an areolar interstitial connective tissue rich in blood vessels (Alm and Stromberg 1974). The fascicles are units of parallel collagen fibril bundles characterised by a uniform waviness (crimp) which play a biomechanical role (Haut and Little 1969, Alm and Stromberg 1974, Yahia and Drouin 1989). There are two wave patterns, planar and helical. The CrCL has a mainly planar pattern seen along the entire fascicle length (Fig. 1.17), usually at right angles to the longitudinal axis (Yahia and Drouin 1989). The collagen fibrils inside the fascicles also have a planar wave whose amplitude decreases towards the core of the fascicle especially in the distal third of the ligament (Alm and Stromberg 1974, Yahia and Drouin 1989). A helical pattern is occasionally seen. The response to tensile stress is a straightening of the wavy fibrils and deformation of the straight ones. if the crimp (wave) is overstretched this causes irreversible damage (Viidik 1972, Yahia and Drouin 1989). Histologically there is no difference between the two CrCL bands (Heffron and Campbell 1978). The cruciate ligaments attach to bone by a direct insertion where there is a transitional zone of fibrocartilage and mineralised cartilage. This helps prevent stress concentration by a gradual change in stiffness (Arnoczky 1983, Frank et al 1985, Burks 1990). There are 4 transition zones (Cooper and Misol 1970, Woo 1988):-

a) wavy collagen

b) fibrocytes become mainly chondrocytes - fibrocartilage.

c) ground substance becomes mineralised

d) bone matrix collagen fibres blend with mineralised fibrocartilage

The synovial membrane covering the cruciate ligaments consists of dense connective tissue and fibroblasts, more cellular than the ligaments (Heffron and Campbell 1978). It has been reported that the surface of the CrCL in contact with the caudal cruciate ligament has no synovial lining and the collagen fibres are denser at this point (Vasseur et al 1985).

VASCULAR ANATOMY.

The main blood supply to the cruciate ligaments comes from the descending genicular and caudal genicular arteries (Tirgari 1978a). The majority of the cruciate ligaments' blood supply is extra-ligamentous with most vessels entering via a synovial sheath rather than a bone-ligament attachment (Arnoczky and Marshall 1981). There is evidence that the main source of nutrition to the cruciate ligaments may be from the synovial fluid (Amiel et al 1986).

Cranial cruciate ligaments. The main arteries enter via synovial folds. Along the proximal caudal fold they enter the ligament and ramify into the paraligamentous membrane, proximal and distal branches, 0.02-0.05 mm diameter, producing a fine network (Alm and Stromberg 1974). Along the distal caudal fold, small arteries enter and ramify proximally (Alm and Stromberg 1974). Arterioles (0.01-0.02 mm) run longitudinally within the epitenon and branch transversely (<0.01 mm) to encircle the collagen bundles. At the femoral origin a few endosteal vessels communicate with epitenon vessels, and a few periosteal vessels connect with paraligamentous vessels. At the tibial insertion there are paraligamentous vessels which connect with epitenon and meniscal vessels but there are few epitenon vessels and they do not communicate with endosteal vessels (Alm and Stromberg 1974). The diameter of the proximal arteries is greater than the distal (Paatsama 1952, Zahm 1965, Alm and Stromberg 1974) and the vessels are larger in the paraligamentous membrane, periphery and core of the proximal ligament than the core of the mid and distal ligament (Zahm 1965, Alm and Stromberg 1974) (in man - Pfab 1927, Davies and Edwards 1948). Paatsama (1952) and Loeffler (1964) found no intrinsic blood vessels, only those in the paraligamentous membrane which they stated could not assist in the regeneration of a ruptured CrCL. However they injected marker dyes of larger particle diameter which may not have been able to enter the smaller intrinsic vessels.

Caudal cruciate ligament. Proximally vessels from the infrapatellar fat pad enter the ligament along the cranial synovial fold (Amiel et al 1990a, Burks 1990) , distally they enter along a caudal fold. There are many connections between the proximal and distal paraligamentous, epitenon and endosteal vessels (Alm and Stromberg 1974). The ligament core has less blood vessels, both in number and size, than the proximal and distal ends but it has more intrinsic blood vessels than the CrCL (Alm and Stromberg 1974, Arnoczky et al 1979, Pfab 1927- in man) although some authors have refuted this (Scapinelli 1968). Similar variations in vascular perfusion have been shown in other tissues; human Achilles tendon (Lagergren and Lindholm 1959), equine superficial digital flexor tendon (Stromberg 1971), human supraspinatus tendon (Rathbun and McNab 1970) where tendon tension was said to cause a reduction in blood flow. It has been suggested that as the cruciate ligaments twist on each other during flexion, compression occurs in the core vessels causing ischaemic embarassment. This may be true to some extent but the core vessels are still less numerous than the peripheral so compression can only compound the reduction in blood flow. There is some evidence to suggest that those areas with fewer and smaller blood vessels (core of the mid part) may degenerate with age (Zahm 1965).

INNERVATION.

The stifle joint nerve supply comes from branches of the tibial and common peroneal nerves. The former supply the cruciate ligaments and most fibres have a vasomotor function. The common peroneal nerve receives sensory information from both the lateral joint capsule and the lateral collateral ligament (Evans 1993b). There are specialised nerve endings in the stifle ligaments and joint capsule which are mechanoreceptors for postural kinaesthetic reception, they allow conscious awareness of joint position, amplitude and velocity (Bennett 1991). The mechanoreceptors act as load cells and may signal impending injury (Barrack and Skinner 1990). Forces causing ligament strain result in the simultaneous relaxation of the quadriceps muscle group and contraction of the caudal thigh muscles, i.e. a protective feedback mechanism attempting to reduce the magnitude of forces antagonistic to CrCL function (see muscles 1.2.2.1.) (Arms et al 1984, Markolf et al 1990). In man, mechanoreceptors similar to Golgi tendon organs have been demonstrated in cruciate ligaments, mainly on the ligament surface near insertion sites (Kennedy et al 1974, Shultz et al 1984).

The turnover metabolism of joint ligaments is one of the slowest in the body and partly explains the reduced healing capacity of these ligaments compared to other connective tissues in the body eg. skin (Viidik and Lewin 1966).

1.3 STIFLE JOINT FUNCTION

The maintenance of normal stifle function depends on the coordinated action of muscles, ligaments, menisci, capsule and other soft tissues as well as the geometry of the femoral and tibial condyles (Trent et al 1976).

The stifle joint has 6 degrees of freedom of motion (3 angular and 3 translational) around 3 axes, x, y, z (Arnoczky 1985) which are limited by ligaments and femoral condylar geometry (Fig. 1.18). The three angular degrees of freedom are flexion/extension, rotation and varus/valgus. There are in addition, 3 translational movements in the 3 planes of the anatomical axes. **x axis** passes through the femoral condyles, medial to lateral, and is the main hinge-like motion of the joint resulting in flexion, extension and craniocaudal translation (drawer) (Hohn and Newton 1975). These movements are limited by the cruciate and collateral ligaments. **y axis** passes parallel to the tibial shaft through the medial tibial plateau and represents internal and external rotation. this motion is limited by femoral condyle geometry and ligament constraints (Arnoczky and Marshall 1981). To achieve rotation the femoral condyles slide on the tibial plateau, one forwards and the other backwards (Goodfellow and O'Connor 1980). Some authors report that the stifle can rotate when the joint is extended (Furman et al 1976, Arnoczky and Marshall 1977), others say not (Paatsama 1952, Kapandji 1970a, Goodfellow and O'Connor 1980, Segal and Jacob 1983 - in man). **z axis** passes craniocaudally through the joint space representing varus and valgus rotation which is limited by the collateral ligaments (Arnoczky 1985).

Functional stability of the stifle joint relies on static and dynamic components; static when the forces and joint position are constant i.e. standing, dynamic when they are changing. Stability is maintained by passive ligament and joint geometry restraints, and active muscle restraints (Arnoczky and Marshall 1981, Biden and O'Connor 1990, Johnson and Johnson 1993). The normal range of joint movement occurs without significantly stretching ligaments or indenting articular surfaces until the limit of range of motion is approached, then ligament tightening and articular surface indentation increases resistance to further movement (Biden and O'Connor 1990).

As the stifle joint flexes the lateral collateral ligament slackens and allows the caudal displacement of the femoral condyles on the tibial plateau (called 'roll-back' by Dye

1988). Due to the geometric, bony asymmetries between the medial and lateral femoral and tibial articular surfaces (1.2.1.1. and 1.2.1.2.) and because the superficial part of the medial collateral ligament remains taut throughout joint flexion (1.2.2.5.), the tibia internally rotates relative to the femur. This movement is reversed with joint extension when the lateral collateral ligament tightens (Hulse and Shires 1985). Immediately prior to full extension the lateral collateral ligament is most taut and the femoral condyles appear to 'sit-down' into the articular condyles on the tibial plateau. This is termed the 'screw-home mechanism'. In dogs, during stifle joint extension there is a nearly equal roll-back of the femur on the tibia in both the lateral and medial compartments, unlike in ungulate and human stifles, due to the greater symmetry in medial and lateral boney geometry which reduces the degree of the 'screw-home mechanism' seen in dogs compared to man near full extension (Dye 1988).
The ligaments which help maintain joint stability have two roles; **passive mechanical joint restraint,** which is important because of the relative incongruency of the articular surfaces (Blankevoort et al 1991), and **dynamic guides to stifle function** (Barrack and Skinner 1990). The cruciate ligaments are dynamic structures and their anatomy and spatial arrangement are directly related to their function (Arnoczky and Marshall 1981).

1.3.1. PASSIVE MECHANICAL RESTRAINT

The tension within the stifle ligaments changes during joint movements and, together with the other soft tissue joint restraints, as excesses of motion are approached, these tensions equilibrate and counter gravitational, inertial and muscle forces causing the joint movement and result in restraint of that motion.

Cranial cruciate ligament. Its most important function is the control of the forward translation (cranial drawer) of the tibia on the femur, that is craniocaudal stability, which is assisted by muscle fascia and joint capsules (Alm and Stromberg 1974). To a lesser degree it prevents excessive internal rotation when the joint is flexed by twisting on the caudal cruciate ligament (Dyce et al 1952) and is also the primary check against hyperextension (Arnoczky 1988, Robins 1990, Payne and Constantinescu 1993).

Caudal cruciate ligament. It is slightly longer and broader than the CrCL with similar functions. It mainly limits caudal drawer of the tibia on the femur (Egger 1983), but also assists in rotational stability and is a secondary restraint to hyperextension. (Arnoczky 1988, Payne and Constantinescu 1993).

Both ligaments contribute to limit joint flexion (Arnoczky and Marshall 1977). The cruciate ligaments twist on each other as the joint flexes to limit internal rotation (Dyce et al 1952). Some authors report that neither cruciate ligament alone limits external rotation (Arnoczky and Marshall 1977), others say they do (Paatsama 1952, Pearson 1969, Rudy 1974a, Hohn and Newton 1975). It has been reported in man that tibial rotation has no significant effect on CrCL fibre length so implying that the twisting of the cruciate ligaments, which would increase fibre length, is resisted by capsule shearing, slanting collateral ligaments and the meniscal and joint surface geometry and the cruciate ligaments exert only a secondary role (Amis 1985). This may be true at greater degrees of joint extension, but as the joint flexes the CrCL appears to play a greater role in limiting internal tibial rotation as shown by the results of severing the joint ligaments sequentially *in vitro* in table 1.1 (Arnoczky and Marshall 1977). As the joint flexes, the cruciate ligaments become stressed by varus or valgus loads and therefore become more important in limiting those motions but are still secondary restraints compared to the collateral ligaments (Monahan et al 1984).

Medial collateral ligament. Mainly prevents valgus but also limits internal and external rotation in joint extension and external only when the joint is flexed (Hohn and Newton 1975, Arnoczky 1985, Hulse and Shires 1985). This difference in rotational restraint is because only the superficial portion of the medial collateral ligament is taut in flexion, the deeper part is relaxed (1.2.2.5.)

Lateral collateral ligament. Prevents varus and limits rotation to a minor degree when the joint is extended (Hulse and Shires 1985, Payne and Constantinescu 1993). In flexion the lateral collateral ligament is slack and will allow internal tibial rotation (1.2.2.5.). It is also reponsible for the minor 'screw-home mechanism' described previously.

The contribution of the stifle ligaments to joint stability can be appreciated by comparing that stability before and after the ligament is sectioned. See table 1 below (Arnoczky and Marshall 1977).

1.3.2. DYNAMIC GUIDE TO STIFLE FUNCTION

The ratio between the lengths of the cruciate ligaments (approx 1:1) and the distance between their femoral and tibial attachments (approximate ratio 1:2) is said to form a

Tchebychev mechanism for parallel motion whereby the length ratios and geometry of the cruciate ligaments, the foundation of stifle joint kinematics, act as a crossed four bar linkage and geometrically determine the shape of the femoral condyles i.e. the condylar shape is dependent on the cruciate ligament geometry and not vice versa (Strasser 1917, Kapandji 1970b, Badoux 1984). The four bar linkage relies on the cruciate ligament remaining taut throughout the range of movements (Goodfellow and O'Connor 1980) and assumes that the ligaments are inextensible (isometric) and attached to the bones at a single point (Steindler 1955, O'Connor and Goodfellow 1989) (Fig. 1.19). However, Amis and Dawkins (1991) showed that in man all fibre bundles lengthened during the last 30 degrees of flexion, none was isometric. The above theoretical geometric model is not universally accepted and it only applies to sagittal motion and ignores rotational movement and the influence of other stifle structures. However, it provides a simplified explanation of the relationship between the geometry of the cruciate ligaments and the articular surfaces.

As the joint flexes the femoro-tibial contact point moves caudally (Fig. 1.19). The axis of flexion (x axis) of the femur relative to the tibia varies during flexion and extension but at any one time there is a point on the femur with zero velocity with respect to the tibia, the instant centre of motion (Frankel et al 1971, Arnoczky et al 1977). In man the instant centre of motion is reported to lie at the intersection of the neutral, isometric cruciate ligament fibres (Strasser 1917, Bradley et al 1988). When this point lies on the articular surfaces there is rolling joint motion with minimal friction. If the instant centre of motion lies on a line perpendicular to the articular surface at joint contact then sliding motion occurs. The normal stifle joint exhibits both (Frankel et al 1971, Arnoczky 1985). If neither of the above occurs, the direction of the velocity of movement at the articular contact point is not a tangent to the articular surfaces which leads to compression or joint separation in addition to sliding (Arnoczky et al 1977). In the CrCL-deficient stifle or one repaired by an intra-articular method, the instant centre of motion is normal. After extra-articular repair the instant centre of motion is abnormal (Arnoczky et al 1977).

1.4 DISCUSSION

The stifle joint has changed very little in millions of years, with many features of the modern joint being recognised in amphibians over 300 million years ago. This means that not only have a diverse range of species similar stifle joint anatomy, but also the most complex joint in the body must be a very functionally efficient design for it to have been changed so little by evolution when other structures have changed so much. Despite many similarities, no species duplicates the canine stifle anatomy exactly and so care must be taken if extrapolating data between species especially from man where a considerable amount of data is available on stifle joint kinematics and biomechanics. Man has a bipedal plantigrade stance where the stifle joint can be and often is fully extended, resulting in a much less CrCL-dependent joint because the resultant forces of weight-bearing are directed through the joint axis and have no craniocaudal shearing forces tending to separate the femur and tibia. Also because the tibial plateau is virtually horizontal there is less tendency for the femur to slide caudal relative to the tibia. The stifle joint of the quadrupedal digitigrade dog, in contrast, is always held at some degree of flexion with the resultant forces running cranial or caudal to the joint axis and so tending towards more joint flexion during weight-bearing. The quadriceps and gastrocnemius muscles contract to stabilise the joint resulting in greater CrCL tension. These effects are compounded by the caudodistal slope of the tibial plateau and lead to a CrCL-dependent stifle (Fig. 1.6).

As well as major hinge-like action, the joint also exhibits rotation of the tibia relative to the femur which is mainly the result of the medial and lateral asymmetries of the articular surfaces of the femur and tibia. During flexion and extension the femoral condyles roll back and forth on the tibial plateau and because the lateral femoral condyle is more convex than the medial and the lateral tibial plateau slopes distally more than the medial there is an uneven roll back and the tibia rotates. The bony geometry of the joint is the main cause of the rotation, soft tissues, namely cruciate ligaments, collateral ligaments, joint capsule, menisci and muscles, limit that rotation to varying degrees at different angles of flexion. The CrCL limits internal rotation most at greater degrees of flexion. In man there are greater medial and lateral asymmetries resulting in a more unequal roll-back and more internal and external rotation.

The cruciate ligaments function reciprocally together, acting as a four bar linkage, to determine the shape of the tibial and femoral articulating surfaces and to guide the changes in areas of contact of those surfaces during joint motion to ensure the correct ratio of sliding and rolling movement throughout flexion and extension (Fig. 1.19). The stifle joint ligaments have complex structures where the cruciate and medial collateral ligaments are each one ligament anatomically but act as two ligaments functionally. Due to the orientation of their attachments, the cruciate ligament fibres twist along their ligament axis. This is more pronounced with joint flexion and leads to different tensions within different portions of the ligaments (Fig. 1.12, 1.13, 1.14, 1.15). These changes with joint flexion and extension result in complex, efficient ligaments which are difficult to study, especially biomechanically (see chapter 7), and are impossible to return to 100% function with reconstructive surgery.

As described, the menisci are important to joint funtion both in reducing joint trauma and wear and tear and also in assisting the cruciate ligaments in joint stability. There are however no anatomical attachments between the CrCL and the menisci, unlike in man.

A reduced blood supply to the CrCL, especially the core, may affect the biomechanical properties of the ligament. These properties are also reported to be influenced by a number of predisposing factors which will be discussed in later chapters.

CHAPTER TWO

MECHANISMS OF INJURY TO THE CRANIAL CRUCIATE LIGAMENT AND ITS DIAGNOSIS

" Vets hope to alter the course of a disease when we understand its origins and development."

Johnson JM and Johnson AL 1993

2.1 INTRODUCTION

Paatsama (1952) reported that rupture of the CrCL is the most common injury in the stifle joint of the dog and this statement still holds true today, 40 years later.

Injury to the CrCL was first described in man by Stark (1850), but 76 years elapsed before the condition was reported in the dog by Carlin (1926). The first surgical repair of the ruptured ligament in man was described by Hey Groves (1917) using the tensor fascia lata for ligament reconstruction. This method is still the basis for some of today's reconstructive surgery techniques. Paatsama (1952) reported the first surgical repair of the canine CrCL.

2.2 PATHOGENESIS OF CRANIAL CRUCIATE LIGAMENT RUPTURE

CrCL rupture is related to its function as a dynamic constraint to joint movement (Robins 1990). The pathogenesis of rupture is multifactorial where no one theory, cause or series of events can explain the mechanism and is therefore controversial (Robins 1990, Johnson and Johnson 1993), but there are two main groupings which can be classified according to signalment and history of the onset of clinical signs. These are **primary acute trauma** and **chronic degeneration** of the CrCL. Because it can sometimes be difficult to assign an individual case to the traumatic or degenerative group, there is a wide variation of opinion in the literature of the proportion of each group seen (table 2.1).

Apart from Tirgari (1978b) and Paatsama (1952) there is a trend towards a greater proportion of degenerative cases in reports from more recent authors. This may be due to a genuine increase in the numbers or an increased awareness of the degenerative cases.

The ultimate causes of CrCL rupture, in either clinical group, are forces acting on the ligament at or near its extremes of constraint (Arnoczky and Marshall 1981). It is only the degree of those forces, underlying causes and predisposing factors which separate the groups. These forces are rarely due to external trauma such as a caudally directed blow to the distal femur, but forces within the joint itself resulting from normal joint loading or incoordinate movement (Fig. 2.1) (Dyce et al 1952).

As described in chapter one, the stifle joint movements limited by the CrCL are primarily forward translation (drawer) of the tibia on the femur, but also hyperextension (Fig. 2.2) and internal tibial rotation as the joint flexes. In hyperextension, the CrCL may contact the cranial femoral intercondylar notch causing direct trauma to the ligament and contribute to its failure (Fig. 2.2) (Slocum and Slocum 1993). Therefore it is during these joint motions that damage to the CrCL can occur.

2.2.1 PRIMARY ACUTE TRAUMA

This is now recognised as occuring only rarely in dogs and is usually seen in young, active animals where a traumatic episode such as a paw caught in a hole during rapid locomotion or a road traffic accident results in sudden stifle joint hyperextension (Fig. 2.2) with or without internal rotation, or internal rotation while the joint is partially flexed at 20-50 degrees (Haut and Little 1969, Rudy 1974b, Arnoczky and Marshall

1981, Arnoczky 1988, Pedersen et al 1989, Robins 1990, Doverspike et al 1993). In both of these stifle joint positions the bulk of the CrCL is at its most taut.

In man CrCL rupture pathogenesis is usually acute traumatic (Palmer 1938, O'Donoghue 1963, Liljedahl and Norstrand 1969, Akeson et al. 1985), commonly seen in footballers and skiers. Isolated rupture is most common in man following hyperextension (Liljedahl and Norstrand 1969).

2.2.2 CHRONIC DEGENERATION OF THE CRANIAL CRUCIATE LIGAMENT

The stifle joint motions resulting in CrCL rupture from chronic degeneration are the same as in the acute trauma group but there is a prior ligament degeneration process which results in the weakening of the CrCL. This ligament weakening means that forces acting on the CrCL, the result of weight-bearing, which are normal in magnitude and direction now act on an abnormal ligament and so these same forces lead to ligament damage and eventual failure. The weakening of the ligament due to intrinsic changes of the microstructure (2.2.3.) may also be influenced by predisposing factors which lead to further ligament degeneration or result in forces of abnormal magnitude and/or direction acting on the CrCL (2.2.4.). The effect of the degenerative processes on the ligament biomechanical properties (structural and material) will be discussed in detail in a later chapter. The normal healthy canine CrCL has been shown to with-stand uniaxial tensile loading of up to four times body weight before failure (Gupta et al 1969) (see chapter 7).

Dogs presented with CrCL rupture sometimes have a prior history of intermittent lameness or stiffness which resolved with rest. Often the owners will then report an acute lameness following normal activities such as level walking or trotting with no history of a sudden traumatic event. Sudden rupture of the CrCL does not classify the disease process in the acute traumatic group, it is just the end result of a more chronic, possibly subclinical process precipitated by minor ligament stresses.

The pathogenesis involves gradual ligament degeneration and weakening resulting in stretching of the ligament, joint laxity and instability which leads to more ligament and joint trauma and finally results in partial followed by complete ligament rupture (Paatsama 1952, Zahm 1965, Campbell 1977, Arnoczky and Marshall 1981, Arnoczky 1983, Arnoczky 1988, de Lahunta and Habel 1986, Bennett et al 1988).
Bilateral CrCL rupture is commonly reported in the literature although there is on average an 8-12 month period between the two ligaments rupturing (Singleton 1969- 17% bilateral, Denny and Minter 1973 - 17%, Denny and Barr 1987 - 14%, Lewis 1974 - 26%, Bennett et al 1988 - 25%, Bennett and May 1991b - 24%, Doverspike et al 1993 - 37%, Slocum and Slocum 1993 - 32%).

2.2.3 MICROSCOPIC CHANGES TO THE CRANIAL CRUCIATE LIGAMENT

A number of changes are seen in the CrCL microstructure as the result of the degenerative processes, whatever the predisposing factors involved. These include a loss of fibroblasts (ligamentocytes), metaplasia of fibroblasts to chondrocytes, failure to maintain parallel collagen bundles, calcium deposits, collagen fibril hyalinisation, loss of fascicular waviness, liquefaction necrosis and karyolysis (Paatsama 1952, Zahm 1965, Vasseur et al 1985). The core of the mid portion of the CrCL is the most affected and it is thought that the degenerative process may, in part, have an ischaemic basis due to fewer and smaller blood vessels in this area compared to the peripheral, proximal and distal areas (Zahm 1965, Alm and Stromberg 1974, Vasseur et al 1985). This is further supported by the reported focal thickening of the intima of the endoligamentous blood vessels (Gilbertson et al 1979).

Another process which may be involved in CrCL degeneration is immune-mediated. A study of canine serum and synovial fluid found that, of dogs with CrCL rupture, 79% had immune complexes in their sera and 69% had immune complexes in their synovial fluid (Niebauer and Menzel 1982). It is the phagocytosis of these immune complexes by polymorphonuclear granulocytes which releases collagenase which in turn erodes joint cartilage and degrades native collagen to immunogenic peptides (Niebauer and Menzel 1982). These may then trigger the production of anticollagen antibodies which have been found in stifle synovial fluid and serum (Niebauer et al 1987, Griffin and Vasseur 1992). It is not known if the immune process contributes to the pathogenesis of CrCL rupture or is a result of the condition. Despite the fact that CrCL rupture is seen bilaterally in some cases (14-37%), if CrCL degeneration were part of a generalised immune-mediated process it would be expected that ligaments in other areas of the body would also show some signs of abnormality. This has not been reported.

Whatever the cause, the degenerative process leads to a decrease in the tensile strength of the ligament (see chapter 7). The caudal cruciate ligament is also affected but to a much lesser degree (Vasseur et al 1985).

2.2.4 PREDISPOSING FACTORS

A number of predisposing factors (signalments) are reported to be associated with CrCL rupture. Although they will be discussed individually, some factors are reported to be inter-related and these will be emphasised where appropriate.

2.2.4.1 AGE

Many authors have maintained that degenerative CrCL disease is seen mainly in middle aged to older dogs, usually over 5 years old with only one peak age incidence at 6-8 years of age (Paatsama 1953, Pond and Campbell 1972 (107 cases), Hohn and Newton 1975, Henderson and Milton 1978, Arnoczky 1980, Shires et al 1984, Vasseur et al 1985, de Lahunta and Habel 1986, Piermattei 1986, Griffin and Vasseur 1992 (49 cases), Doverspike et al 1993 (114 cases), Whitehair et al 1993 (10,769 cases)). Others report two peak age incidences, one at 2-3 years, the other at 6-8 years (Singleton 1969 (88 cases), Denny and Minter 1973 (159 cases), Lewis 1974 (62 cases), Hulse et al 1980, Bennett et al 1988 (111 cases), Bennett and May 1991b, Robins 1990, Slocum and Slocum 1993 (394 cases), Vasseur 1993). Bennett et al.(1988) reviewed the cases presented at the referral hospital at Liverpool in recent years, 65 cases between 1970 and 1974, and 111 cases between 1985 and 1988. They found a change in the referral population over these two periods from dogs with a peak age incidence at 4-5 years to ones with a peak at 1-2 years (there was also a trend towards larger breeds). There is no consensus on the effect of age on CrCL degeneration and strength. Some authors have shown that ligament microstructure-changes increase with age, especially in those over 5 years old and also in larger dogs (Zahm 1965, Vasseur et al 1985) and that the ligament's mechanical properties are affected by age (Noyes and Grood 1976, Tipton et al 1978, Vogel 1978). Others have found no evidence of degeneration and weakening of the CrCL with age (Tirgari and Vaughan 1975, Alm et al 1974 - although this latter study only involved dogs aged 11-14 months).

Partial rupture has been reported more frequently in young (and large) dogs (Griffin and Vasseur 1992, Johnson and Johnson 1993).

2.2.4.2 SIZE, WEIGHT AND OBESITY

There is no clear distinction between the size, weight and breed groups as these parameters are not mutually exclusive and their inter-relationships should be considered when discussing the disease pathogenesis.

A number of studies have reported a correlation between the size of a dog and the incidence of CrCL rupture. Earlier authors have described the affected population as being small to medium breeds (Singleton 1969, Hohn and Newton 1975). Others, especially more recently, have reported an increase in the numbers of larger breeds and younger animals being presented with CrCL rupture (Arnoczky and Marshall 1977, Vasseur 1986, Bennett et al 1988). Lewis (1974) reported that CrCL rupture occured younger in the larger breeds but the incidence of the disease was still greater in small and medium breeds.

Obesity reportedly predisposes to CrCL disease although in most studies the authors giving individual body weights do not state which are obese (Lewis 1974, Rudy 1974b, Henderson and Milton 1978, Pedersen et al 1989). However, in a study of 114 cases (Doverspike et al 1993), 84% were over 15kg body weight and of these, 35% were considered overweight. Vasseur et al (1985) showed greater ligament microstructure degeneration in dogs over 15kg body weight as well as in those over 5 years old, although they found that the larger the dog the greater the degeneration at a younger age. They did not detail which dogs, if any, where obese.

The rate of the degenerative changes in the joint following CrCL rupture is proportional to the weight (and activity) of the individual because the heavier the dog, the greater are the damaging abnormal gliding and shearing forces on the remaining joint structures (Pedersen et al 1989).

2.2.4.3 CONFORMATION

Various conformational abnormalities have been suggested as contributary factors to the pathogenesis of CrCL rupture, although despite numerous references to conformation, very little beyond general headings of abnormalities have been reported. The conformational variances described are straight stifles, straight hocks, varus, valgus, patella luxation (Rudy 1974b, Hohn and Newton 1975, Arnoczky and Marshall 1981, Arnoczky 1983, Arnoczky 1985, Vasseur et al 1985, Bennett et al 1988, Johnson and Johnson 1993). The effect of these abnormalities is to put an abnormal and/or increased stress on the ligament as the normal biomechanical loading of the joint is altered. This repeated stress loading which is abnormal in magnitude or direction may result in a gradual decrease in the material properties of the ligament substance (see chapter 7). Medial patella luxation results in the malalignment of the quadriceps muscle group via the straight patella ligament which tends to internally rotate the tibia and increase the load on the CrCL (Doverspike et al 1993).

2.2.4.4 SEX

There is no consensus as to the degree that gender predisposes a dog to CrCL disease. In a comprehensive study of 10,769 cases in the USA there was a greater prevalence in females compared to males (Whitehair et al 1993). This agrees with the findings of Denny and Minter (49 cases- 58% female-1973), Bennett et al (111 cases-58% female-1988), Griffin and Vasseur (49 cases-67% female-1992), Doverspike et al (114 cases-66% female-1993), Slocum and Slocum (394 cases-60% female-1993). Others have found no sex differences Singleton (88 cases 1969), Pond and Campbell (107 cases 1972), Lewis (62 cases 1974), Bennett and May (70 cases 1991b). Also reported is a greater prevalence in neutered compared to entire dogs, especially females (Whitehair et al 1993). Two factors may explain this greater prevalence in females, both entire and neutered. Firstly females, especially spayed, are more likely to be obese than male dogs and obesity predisposes to CrCL rupture (see 2.2.4.2). Secondly, sex hormones, namely oestrogens and relaxin. The exact mechanism by which oestrogen affects collagen is not fully understood. It is thought to affect the synthesis and degradation rates of collagen and results in a reduction in soluble collagen. Oestrogen may act either as a collagen synthesis inhibitor or a collagen cross-link inhibitor (Amiel et al. 1990b). Relaxin is a hormone secreted by a bitch immediately prior to whelping which increases the water and mucin content of connective tissue (including ligaments) especially at the pelvic symphysis to allow a minor increase in the diameter of the birth canal. Experimentally, Shikata et al (1979) showed that spayed rats (ie. lacking oestrogen-producing ovaries) had reduced joint capsule elastin and reduced collagen synthesis in their tail tendons. Collagen limits the deformation of the elastic elements of connective tissue and is largely responsible for the tensile strength of the composite structure, and so reduced collagen synthesis may lead to increased laxity in joint ligaments. There is, however, no evidence as to the effects of oestrogens on the ligament substance of dogs under normal physiological conditions.

2.2.4.5 EXERCISE

Exercise has an influence on both the acute traumatic and the chronic degenerative cases but in different ways.

Acute traumatic rupture is related to active, well exercised dogs.

Chronic degenerative rupture is reportedly seen in less active, sedentary dogs (Henderson and Milton 1978, de Lahunta and Habel 1986, Piermattei 1986). The lack of exercise decreases the mechanical strength of the ligaments and results in a reduction in muscle, tendon and ligament joint support (Noyes et al 1974b, Johnson and Johnson 1993). It has also been suggested that inadequate exercise in puppyhood may predispose to ligament weaknesses at maturity (Bennett et al 1988, Johnson and Johnson 1993). Inactivity has been shown to influence the rupture of the CaCL in broilers (Duff 1986).

Following CrCL rupture, the rate of progression of the degenerative joint changes is proportional to the amount of exercise done. The more exercise, the more joint trauma and so the more joint changes.

2.2.4.6 DIET AND SUPPLEMENTATION

There are no scientifically based reports of an influence of diet on the pathogenesis of CrCL rupture, only anecdotal suggestions which probably relate back to the different feeding regimes of large and small breeds of dog, especially prior to maturity.

2.2.4.7 HEREDITY

Very little has been reported regarding a predisposing hereditary basis to CrCL rupture per se, although Vasseur et al (1985) observed CrCL rupture, often bilateral, in an increased percentage of offspring from certain Rottweiler bitches. Breed conformation is genetically controlled. Therefore conformation, which has already been discussed (2.2.4.3.), must be inter-related with the heredity predisposing factor.

2.2.4.8 BREED

Breed is an umbrella group which is directly related to size, weight, gait, conformation and hereditary predisposing factors. Although the general size of affected dogs is usually reported (2.2.4.2.), fewer studies detail the prevalence of CrCL rupture in a particular breed, mainly because the 'at risk' population is often unknown. The 'at risk' population is usually taken as either the total number of all breeds of dog presented at a clinic, whatever their disease condition (as Whitehair 1993), or the total number of a particular breed in the general population, both healthy and unhealthy. Some authors state that there is no breed predisposition and any over-representation is due to the coincidental popularity of the breed (Paatsama 1953, Singleton 1969, Denny and Minter 1973, Shires et al 1984, Bennett et al 1988-although 13.5% of his cases were Rottweilers, Robins 1990 , Elkins et al 1991, Slocum and Slocum 1993-although 5.6% of his cases were Rottweilers). However, Whitehair et al (USA - 1993), reviewing 10,769 cases from an 'at risk' population of 591,548 dogs, found a high prevalence in Rottweilers, Newfoundlands and Staffordshire Terriers. Humphreys (Australia- 1975) found an above average incidence in Beagles, Corgis, Chihuahuas, Whippets and Australian Terriers.

2.3 DIAGNOSIS OF CRANIAL CRUCIATE LIGAMENT DAMAGE

2.3.1 SIGNALMENT

The dog may exhibit one or more of the predisposing factors discussed earlier in the chapter. Age, obesity, breed and size, athletic or sedentary life style.

2.3.2 HISTORY

Acute traumatic rupture may have a history or other clinical signs of a road traffic accident or a sudden traumatic episode resulting in hyperextension of the joint or excessive internal rotation of the tibia. Chronic degenerative rupture will have a more variable history ranging from acute lameness whilst exercising normally with no previous indications of disease to intermittent lameness and a reluctance to rise, improving when rested and possibly progressing to acute severe lameness.

2.3.3 GAIT AND STANCE

Whilst standing the digits of the affected limb are lightly rested on the ground. During locomotion, in small breeds the limb is often carried and bears no weight, in larger dogs the individual will usually weight-bear reluctantly but limp to varying degrees often keeping the hock hyperextended to reduce the caudal traction force on the femur resulting from gastrocnemius muscle contraction (see chapter 1). As the speed of locomotion increases the dog is less likely to bear weight on the affected limb.

2.3.4 CLINICAL EXAMINATION

Degenerative joint disease (DJD) of the stifle joint is a condition commonly found, both clinically and radiographically, following CrCL rupture.

Degenerative joint disease (DJD) or osteoarthritis is a chronic, non-inflammatory disorder of diathrodial joints which has been identified even in dinosaur fossils of 200 million years ago (Arnoczky 1985). There are many causes of DJD although it often occurs following the rupture of the CrCL as a result of the ligament insufficiency causing joint instability and an abnormal concentration or direction of forces on a normal articulation, leading to chondromalacia, dehiscence and fibrillation of articular cartilage (Arnoczky 1985, Pedersen et al 1989, Robins 1990), and eburnation of subchondral bone (Pedersen et al 1989). Joint pain, periarticular osteophytes (Fig. 2.5), capsular thickening and meniscal damage are also present in stifle DJD. The degree of

DJD present is reported to be directly proportional to body size, obesity and activity (Heffron and Campbell 1979, Piermattei 1986, Pedersen et al 1989, Robins 1990, Elkins et al 1991), and it may be established even before rupture is complete in chronic degenerative cases where the ligament has become stretched and lax (Dupuis and Harari 1993).

The findings of the clinical examination will depend on the duration of the disease process, and whether the ligament is partially or completely ruptured.

1) Joint effusion is a common finding and is palpable either side of the patellar ligament (Tirgari 1978b). In experimentally induced CrCL rupture there are differences in the degree of the subsequent synovitis and synovial fluid production observed which may be related to the amount of ligament haemorrhage at the time of sectioning (Myers et al 1990).

2) Firm thickening of the stifle joint on the medial side, especially where the medial collateral ligament is attached to the medial meniscus (Hohn and Newton 1975, Pedersen et al 1989).

3) Reduced range of stifle joint motion.

4) Joint crepitus on flexion and extension. This includes the 'clicking' associated with meniscal movement although the menisci may not necessarily be visibly damaged.

5) Joint pain on palpation and manipulation.

6) Disuse muscle atrophy. The circumference of the thigh is often reduced on the affected side, usually the quadriceps group is most affected. A neurogenic component to this muscle loss has also been proposed (Robins 1990).

2.3.5 DIAGNOSTIC TESTS

2.3.5.1 CRANIAL DRAWER TEST (Fig. 2.3)

This was first described by Schroeder and Schnelle (1941). It assesses the craniocaudal stability of the stifle joint and so examines the integrity of the CrCL. With the dog in lateral recumbency, the thumb is placed on the lateral fabella and the forefinger on the patella. The forefinger and thumb of the other hand are placed on the tibial crest and the fibula head respectively. Holding the femur still, an attempt is made to move the tibia cranially and caudally. When there is cranial movement the test is positive and is indicative of the likelihood of CrCL rupture (Henderson and Milton 1978). A cranial drawer of up to 1cm can be elicited in large dogs (Pond and Campbell 1972). It is advisable to do this test at various angles of flexion from 30 to 90 degrees if one angulation proves inconclusive because in some cases the degree of instability varies with the flexion angle especially with partial ruptures where either the caudolateral or, more commonly, the craniomedial bands may be involved (Scavelli et al 1990- 80% involved the latter). In normal, young, large breeds there is often some cranial drawer movement but it has a sharp cut-off unlike the diseased joint where it is soft. Some authors report this 'normal' cranial drawer in large breeds less than 18 months old (Bennett et al 1988), others only in dogs less than 9 months old (Stead 1993). A false positive result may be induced if the caudal cruciate ligament is ruptured and the tibia is already positioned abnormally caudal to the femur prior to testing (Butler et al 1980). A false negative result is possible if the secondary restraints to cranial movement (collateral ligaments and the middle third of the medial and lateral joint capsule) block the cranial drawer motion at the small manual forces used in the test (45-90N) (Butler et al 1980). Thickening of the secondary restraints probably accounts for the clinical findings of Singleton (1969) that led him to state that partially ruptured CrCLs can regenerate (Heffron and Campbell 1978).

2.3.5.2 TIBIAL COMPRESSION TEST (Fig. 2.4)

The forefinger is placed on the tibial crest and the other fingers and thumb hold the femoral condyles. The other hand holds the metatarsus and, whilst pressing the tibial crest caudally, the tarsus is flexed and extended. If the tibia appears to move cranial relative to the femur as the tarsus is flexed, this is a positive result indicating CrCL insufficiency. This test simulates gastrocnemius muscle contraction which is antagonistic to CrCL function and in the case of CrCL insufficiency, the caudodistal distraction force created will pull the femur caudally (see chapter 1) (Henderson and Milton 1978). This test rarely causes pain and is useful in larger dogs where limb size may make it difficult to perform the cranial drawer test correctly.

Both hindlimbs should be examined and compared in the two tests to allow for inevitable individual variation.

It may be necessary to sedate or anaesthetise the subject to carry out the cranial drawer test effectively but this is not usually required for the tibial compression test.

2.3.5.3 SYNOVIAL FLUID ANALYSIS

This is an invasive technique requiring aseptic arthrocentesis and involving the examination of the fluid for colour, mucin clot, cell count and type. The results will vary depending on the degree of CrCL damage present. In a study by Griffin and Vasseur

(1992) the mean nucleated cell count from the synovial fluid of dogs with complete (n=33) and partial (n=15) CrCL rupture were 1417 and 3257 cells/mm^3 respectively. The number of neutrophils were 67 and 448 cells/mm^3 respectively. Both the nucleated cell count and the number of neutrophils in the canine synovial fluid were statistically significantly higher (z-test) in those with partial compared to complete CrCL rupture. The findings of Griffin and Vasseur (1992) agree with other authors (Lipowitz 1985, Pedersen 1989) and indicate that following a partial rupture the synovial fluid is mildly inflammatory whereas it is non-inflammatory following chronic and complete rupture (Miller et al 1974, Lewis et al 1987, Pederson et al 1989, Griffin and Vasseur 1992). Yellow-tinged synovial fluid often indicates an increased protein level, either soluble or cellular, in the fluid. It may also indicate previous haemorrhage and haemoglobin release into the synovial fluid (Pedersen 1978) in which case red blood cells are often seen on cytological examination.

2.3.5.4 RADIOGRAPHY

The severity of the stifle joint changes seen on X-ray will depend on the degree of stifle joint instability, the duration of the disease process and the proportion of soft tissue compared to osseous changes present.

1) Increased joint effusion (synovial fluid) results in the cranial displacement of the infrapatellar fat pad and the distension of the caudal joint capsule (Johnson and Johnson 1993, Vasseur 1993). Increased radio-opacity of the infrapatellar fat pad is often seen (Brinker et al 1990).

2) Osteophytes (Fig. 2.5). The exact mechanism of osteophyte formation is unknown but it is thought to be related to the repeated stretching of the synovial membrane at its osseous attachments, resulting in vascular proliferation and new bone formation (Tirgari 1978a, Pournaras et al 1983). Following CrCL rupture, most osteophytes are seen as periarticular lipping on some or all of these areas:- a) trochlear groove and ridges, b) tibial plateau and caudal tibia, c) proximal and distal poles of the patella, d) caudal femur near the joint capsule attachment, e) margin of the intercondylar fossa (Bennett et al 1988).

Most authors report that osteophytes are detectable radiographically approximately three weeks after the CrCL rupture (Paatsama 1952, Marshall and Olsson 1971, Elkins et al 1991, Korvik 1991, Doverspike et al 1993) although peri-articular osteophytes around the trochlea have been observed intra-operatively as early as 14 days after CrCL rupture (Elkins et al 1991). Histological changes in the articular cartilage have been reported 7 days after experimental sectioning of the CrCL in beagles (Stockwell et al 1983). The articular surface is roughened and less distinct and the collagen fibrils are reduced in diameter and appear more widely spaced (Stockwell et al 1983). Orford et al (1983), however, reported no changes in the articular cartilage until 42 days post-sectioning. Using electron microscopy, changes to the articular cartilage have been observed as early as 2-4 days following experimental sectioning of the CrCL. The collagen fibres near the surface of the articular cartilage had been disrupted resulting in spreading of the fibres (Stead 1994).

It has been suggested that chronic disease in one limb leads to vascular changes in the contralateral limb and the remodelling of boney epiphyses (Gilbertson 1975). Campbell et al (1982) experimentally sectioned the CrCL of one stifle and found no osteophytes in the contralateral stifle 29 months later.

Stressed radiographs may show the cranial subluxation of the tibia relative to the femur but the abnormal joint should always be compared to its contralateral partner.

2.3.5.5 ARTHROSCOPY

This technique of directly inspecting the joint with an endoscope is used more in man as it requires expensive equipment, specialised operators and it can only be used in dogs weighing over 6 kg due to the limitation of the size of stifle joint (Person 1985, Johnson and Johnson 1993).

2.3.5.6 MAGNETIC RESONANCE IMAGING (MRI)

This non-invasive diagnostic technique is used in man and is fast becoming one of the methods of choice. It relies on the identification of a sigmoid caudal cruciate ligament to diagnose a ruptured CrCL and it correlates to 95% with arthroscopic findings. MRI is not used widely in dogs due to the unavailability of the necessary equipment (Polly and Callaghan 1988, Boeree and Ackroyd 1992, Johnson and Johnson 1993).

2.3.5.7 ARTHROTOMY

In some cases an arthrotomy is the only way to definitively confirm the diagnosis and is often used to examine the joint fully for damage to other joint structures especially the medial meniscus which is damaged in a high percentage of cases of CrCL rupture.

Approximately 50% of dogs with CrCL rupture also have some degree of damage to the medial meniscus (Flo 1990, de Lahunta and Habel 1986, Pedersen et al 1989, Scavelli et al 1990 (61% with complete rupture and 20% with partial), Bennett and May 1991a), although one report was only 7% (Denny and Barr 1987). The menisci are damaged when they are exposed to abnormal pressures resulting from the joint instability and the unphysiological gliding and shearing of the tibia and femur (Arnoczky and Marshall 1981). There is a normal concentration of force on an abnormal articulation (Pedersen et al 1989). The cartilage matrix degenerates and the collagen bundles fragment resulting mainly in meniscal tears (Arnoczky and Marshall 1981). The medial meniscus is more frequently damaged than the lateral because it is less mobile and so it is trapped and injured when the femur rotates near extension (Shute 1969, Hohn and Newton 1975). Also excessive CrCL-deficient joint manipulation during the cranial drawer test may damage the meniscal attachments and lead to abnormal displacement of the menisci (Stone et al 1980).

At arthrotomy the CrCL may look functional but there is a stage when the ligament appears macroscopically intact but microscopically the collagen fibres are disrupted (Kennedy et al 1976). Biomechanically the ligament has moved from the reversible elastic deformation to the irreversible plastic phase during loading (see chapter 7). Partial CrCL rupture is diagnosed less frequently than complete (Tirgari et al 1975 - 2 of 150, Tirgari 1977 - 3 of 64, Scavelli et al 1990 - 25 of 320, Griffin and Vasseur 1992 - 15 of 49, Slocum and Slocum 1993 - 97 of 394). This is probably due to the greater difficulty in diagnosis (Arnoczky and Marshall 1977, Heffron and Campbell 1978) and because many dogs are only presented once the rupture is complete and the clinical signs are more severe, although it appears from the literature to have been diagnosed more frequently in recent years. This is probably because of an increased awareness of the early stages of the condition.

It is important to assess any other joint structure injuries so they can be corrected at the time of the CrCL repair because failure to do so will usually lead to continued lameness following CrCL reconstruction and an increased progression of DJD changes in the stifle. Although no current method of CrCL repair will prevent the development and progression of DJD (Elkins et al 1991), Pearson (1971) reported that the occurrence of DJD is significantly higher in dogs treated by conservative methods when compared to those where good, surgical techniques are used to stabilise the joint. Heffron and Campbell (1979) however found no such difference in the degree of osteophyte formation following conservative or surgical treatment.

2.4 DISCUSSION

Cranial cruciate ligament disease has been recognised for three quarters of a century but its pathogenesis is still not fully understood, probably because of the multiplicity of factors involved.

Two distinct disease processes are now recognised; acute traumatic and chronic degenerative. The latter is being increasingly diagnosed since ligament degeneration was demonstrated by work on the ligament microstructure by Paatsama (1952), Zahm (1965), Alm and Stromberg (1974) and Vasseur et al (1985) and the improvement in ligament strength testing procedures. There can be some confusion because the rupture mechanism is fundamentally the same in both processes and usually has an end result of acute lameness, but in the degenerative cases either the forces on the CrCL are abnormal in magnitude and/or direction or the ligament substance is weakened but the forces are normal, or both. Hyperextension or internal tibial rotation while the joint is flexed are the most common stifle joint positions resulting in CrCL rupture.

There is a relatively high percentage of cases of bilateral CrCL rupture (14-37%) which indicates that the increasingly diagnosed chronic CrCL degenerative process is probably influenced by factors which affect the stifle joints bilaterally rather than unilaterally. These factors have been discussed as immune-mediated mechanisms (2.2.3.) and/or predisposing factors (2.2.4.) Both the former and the latter will affect both stifle joints, but an immune-mediated process would be expected to result in a more generalised effect on body ligaments, although the unique function of the cruciate ligaments in maintaining the stability of the most complex joint in the body whilst it is repeatedly

loaded during flexion and extension may explain a tendency to affect the cruciate ligaments in preference to other ligaments.
Cranial cruciate ligament rupture is seen increasingly in young, large breed dogs rather than the traditional small and medium sized 6-8 year olds. The reports of clinical case records should be interpreted carefully as most are the result of data collation from referral centres at veterinary schools and can be expected to have a biased sample population (Lewis 1974 - Liverpool, Denny and Barr 1987 - Bristol, Bennett et al 1988 -Liverpool). Whitehair et al (1993) studied data from 23 USA veterinary schools but they did not record if they were first opinion clinics or referral centres only.

The distinction between breeds is determined, in part, by the differences in their gait, conformation and size. For example, Rottweilers are large, well built and have relatively straight stifles and hocks. In contrast, German Shepherd Dogs are also large but they have flexed stifles and walk with their lumbosacral region sloping markedly downwards. Therefore if certain sizes, body weights, gaits or conformations predispose to CrCL disease, then it would be expected that the breeds exhibiting these characteristics would be more prone to the condition. There may also be hereditary factors involved which would affect particular breeds and breed lines. The presence of one predisposing factor may exacerbate the effect of another, eg. conformation and body weight. A dog with medial patella luxation has abnormal resultant forces on the CrCL, due to the deviation of the straight patellar ligament, which will become greater in magnitude if the dog is concurrently overweight.

The process of diagnosing CrCL disease is well documented and consists of testing the integrity of the ligament by examining its resistance to forces antagonistic to its function (cranial drawer and tibial compression tests) and looking for pathological signs of a non-functioning CrCL, that is - joint instability as well as signs of degenerative joint disease, whether primary or secondary.

The treatment of CrCL rupture comprises conservative, extra-capsular and intra-capsular repairs. Detailing the numerous documented procedures is beyond the scope of this work. It is sufficient to say that there is no perfect repair system available and in this disease condition, prevention is definitely better than cure!

CHAPTER THREE

BREED DISTRIBUTION OF CANINE CRANIAL CRUCIATE LIGAMENT DISEASE IN THE UNITED KINGDOM

3.1 INTRODUCTION

The predisposing factors associated with canine cranial cruciate disease were discussed in chapter 2. These included breed, age, weight and sex. Summaries of the findings of various studies, which reported on clinical cases, were given in section 2.2.4.

Although Denny and Minter (1973) reported that Rottweilers with cranial cruciate ligament disease represented only 1.9% from a series of 159 case records and Lewis (1974) reported no Rottweiler cases in their series of 62, more recent studies have shown a greater number of Rottweilers as a percentage of all cases of cranial cruciate ligament disease seen (United Kingdom, - Denny and Barr 1984 - 8.9%, Denny and Barr 1987 - 14.7%, Bennett et al 1988 - 14.4%, Bennett and May 1991b - 24.3%. United States of America, - Slocum and Slocum 1993 - 5.6%, Whitehair et al 1993 - 2.3%).

None of the above studies detailed the relative popularity in the general, healthy dog population, of the different breeds which is required to discuss the significance of the number of dogs of each breed seen with the condition.

Another method of examining the importance of the numbers of different breeds seen, is to assess the 'prevalence' of a disease condition in a specific dog population. For this, the 'at risk' population must be determined (Whitehair et al 1993).

For example, the 'prevalence' of a certain breed of dog to cranial cruciate ligament disease is the number of dogs of that breed presented with the disease divided by the number of dogs of that breed presented with any disease condition ('at risk' population).

The 'at risk' population, as defined above, was not available in this study. Therefore the data is presented, in this chapter, by comparing the incidence of cranial cruciate ligament disease of each breed as a percentage of the total number of dogs of all breeds with the condition.

The age, weight and sex distribution of dogs with cranial cruciate ligament disease have also been reported in UK and USA studies.

The reported mean ages of all breeds of dog seen with cranial cruciate ligament disease were similar in all the studies of clinical cases, whether they are more or less recent reports (UK - Denny and Minter 1973 - 5.7 years, Denny and Barr 1987 - 4.5 years, Bennett et al 1988 - 4.1 years, Bennett and May 1991b - 3.8 years, Stead et al 1991 - 4.8 years. USA - Doverspike et al 1993 - 5.2 years). In those studies where Rottweilers were seen, their mean ages were also similar and were always younger than the mean ages for all the breeds (Bennett et al 1988 - 2.5 years, Bennett and May 1991b - 2.1 years).

A number of authors reported two peak ages for cranial cruciate ligament disease, a maximum peak at 5 - 7 years and a lesser peak at 2 years (UK - Singleton 1969, Denny and Minter 1973, Lewis 1974. USA - Robins 1990, Slocum and Slocum 1993). The study by Denny and Barr (1987) contradicts this, they reported a maximum age peak at 2 years and a lesser peak at 7 years. Pond and Campbell (1972) reported a single peak at 5-8 years, Whitehair et al (1993) at 7-10 years.

The weight of those dogs presented with cranial cruciate ligament disease have been reported by some authors. The mean weights for all breeds were; Denny and Barr (1987) - 35kg, Bennett et al (1988) - 29.9kg. The mean weights for Rottweilers alone were recorded by Bennett et al (1988) as 43.8kg.

A number of studies have reported the sex distribution of those dogs presented with cranial cruciate ligament disease. Some report the condition equally in females and males (Singleton 1969, Pond and Campbell 1972, Lewis 1974), others report a greater number of females than males (Denny and Minter 1973, Bennett et al 1988, Doverspike et al 1993, Slocum and Slocum 1993).

The aim of this section of the study was to determine the breed incidence of cranial cruciate ligament disease in dogs in the United Kingdom and compare it to the relative breed popularity in the general dog population, looking for any breed predisposition to the condition.

3.2 METHOD

3.2.1 BREED POPULARITY IN THE UNITED KINGDOM

The numbers of new registrations and the relative popularity of breeds of dog, as a percentage of all newly registered dogs, in the United Kingdom were determined from the Kennel Club's Comparative Tables of Registration for the years 1969 to 1993 inclusive.

An estimate of the total number of registered dogs of each breed in 1991-1992 was determined by taking an average life span of 10 years and totalling the annual new breed registrations for the years 1983 to 1992 inclusive.

3.2.2 BREED INCIDENCE OF CRANIAL CRUCIATE LIGAMENT DISEASE IN THE UNITED KINGDOM

3.2.2.1 RANDOM GENERAL PRACTICE SURVEY

An eighteen month, prospective survey of cranial cruciate ligament disease in general practice was undertaken between June 1991 and December 1992.
From a total of 2155 general practices, three hundred were randomly selected by taking 300 random numbers from appropriate tables (Lentner 1982). These numbers were matched with an alphabetical list of all general practices (small animal and mixed) in the UK.

A questionnaire (fig 3.1) was sent out to each practice to be filled in whenever a case of cranial cruciate ligament disease was diagnosed over an 18 month period.

3.2.2.2 UK VETERINARY SCHOOLS

The case records of canine cranial cruciate ligament disease seen at four UK Veterinary Schools were studied retrospectively to determine the breed incidence of the condition. The case records of Edinburgh, Cambridge, Bristol and Glasgow were examined.

For the Glasgow data, only the total number of dogs undergoing surgery for cranial cruciate ligament rupture and the number of Rottweilers in that total were known. No further breed breakdown was available.

Of the Veterinary Schools examined, only Edinburgh has a first opinion clinic in addition to a referral service.

3.3 RESULTS

3.3.1 BREED POPULARITY IN THE UNITED KINGDOM

Table 3.1 shows the number of new dogs, of all breeds, registered with the Kennel Club in the years 1969 to 1993 inclusive. The number of new Rottweilers and the percentage of the newly-registered dog population they represent are given. The four most popular breeds over the last 24 years are also illustrated as a percentage of the number of newly registered dogs, to compare with the popularity of Rottweilers. Between 1969 and 1988, the number of newly registered dogs remained relatively static. A large increase in the number of newly registered dogs was seen in 1989 which has been maintained over recent years. The number of newly registered rottweilers increased dramatically between 1969 and 1989, from 163 to 10341 dogs, a jump from 0.1% to 5.0% of the population of newly registered dogs in 1987. Between 1989 and 1990, there was a noticable decline in newly registered Rottweilers from

10341 to 3597 (3.6% to 1.3%). This appears to coincide with a period of negative publicity for the breed.

The relative popularity of newly registered Labradors and Golden Retrievers has increased gradually during the period illustrated. German Shepherd Dogs and Yorkshire Terriers have enjoyed two peaks of popularity in the past 24 years. Between 1986 and 1988, the percentage of newly registered Rottweilers in the dog population were similar to the percentage of newly registered Yorkshire Terriers.

Table 3.2 shows the accumulative total of newly registered dogs between the years 1983 and 1992 which mirrors the popularity of the breeds newly registered annually and illustrated in table 3.1.

The total number of Racing Greyhounds in the UK is unknown, but it has been estimated at approximately 30,000 dogs.

It should be noted that the resulting figures do not represent the total number of each breed, newly registered or accumulative total, in the UK because they do not include the unregistered purebred dogs in the general population, nor do they include crossbred dogs. Therefore, the breed popularity of the entire canine population of the United Kingdom is unknown, but given the large number of registered dogs, it is assumed that the breed popularity of registered breeds reflects a similar breed popularity in the unregistered dogs.

To estimate the total number of each breed in the general population, an average life span was taken as 10 years for all the breeds illustrated in table 3.2 which may be an overestimate in some breeds and an underestimate in others.

3.3.2 RANDOM SURVEY

Of the 300 questionaires sent out, 72 (24 %) positive responses were received. In this study, positive responses were those where data was returned.
The location of those general practices which returned the questionnaire are illustrated in figure 3.2.

The data from all 72 practices were combined to give mean data on canine cranial cruciate ligament disease in general practice and is shown in table 3.3.

Table 3.4 illustrates the breeds presented with cranial cruciate ligament disease at the 72 general practices randomly surveyed.

A total of 821 cases of cranial cruciate ligament disease, in sixty six breeds (including crossbreds) were reported from 72 general practices. Of these, 77 (9.4%) were Rottweilers. No Racing Greyhounds presenting with cranial cruciate ligament disease were reported.
Using a χ^2 test, there were statistically significantly more cases of cranial cruciate ligament disease observed in Rottweilers than could be expected from their percentage popularity in the general dog population ($p<0.001$). Of the other breeds

illustrated in table 3.1, the numbers of Labradors, Yorkshire Terriers and Golden Retrievers presented with the disease were not statistically significantly different than would be expected from their percentage popularity in the dog population ($p=0.11$, $p=0.34$, $p=0.46$ respectively). In contrast, the number of German Shepherd Dogs observed with the disease was statistically significantly lower ($p<0.001$) than could be expected from their percentage popularity in the dog population.

The mean age at onset of clinical signs of the disease was 7.1 years for all the breeds, but it was only 4.6 years in the Rottweilers. Figure 3.3 shows the number of dogs of all breeds and the number of Rottweilers only, in different age ranges. At the onset of cranial cruciate ligament disease, the greatest number of dogs presented, of any breed, was in the 6-8 year old age group. In the Rottweiler, the greatest number was in the 2-6 year old age group. The mean age of all the dogs at the onset of cranial cruciate ligament disease (7.1 years) was statistically significantly greater (t-test - $p<0.001$) than the mean age of the Rottweilers alone (4.6 years).

The mean weight of all the cases was 24.5 kg, but the mean weight of the affected Rottweilers was 45.9 kg. Figure 3.4 shows the number of dogs of all breeds and the number of Rottweilers only, in different weight groups. The greatest number of dogs presented with cranial cruciate ligament disease, of any breed, was in the 2-10kg weight group. In the Rottweiler, the greatest number was in the 42-50kg weight group.

The percentage of male dogs affected was 42.7 % for all the breeds together, but it was 55.6 % for the Rottweilers alone. There was no statistically significant difference (χ^2 test) between the number of male and female Rottweilers presented with cranial cruciate ligament disease ($p=0.30$). However, when all breeds were examined, there were statistically significantly more females seen than males ($p<0.001$). There was a similar proportion with either the left or right limb affected in all the cases and in the Rottweilers alone. However, the number of Rottweilers with bilateral disease, either presented concurrently or with subsequent disease manifestations up to one year later, was greater (17.8 %) than for all the breeds together (10.9%).

Fig. 3.5 shows the number of dogs, all breeds and Rottweilers only, which were presented each month during the 18 month period of the prospective survey.

There were less cases reported in all breeds in September to December 1991 inclusive compared to the 3 months before and 5 months after. However in 1992 more cases were reported monthly in September and October compared to June, July and August that year and September and October in 1991.

Therefore there is no seasonal trend to CrCL rupture as determined by the random survey.

It should be noted that the survey relied on general practitioners consistently and accurately recording the data requested on the questionaire form over an 18 month period. Inadvertently forgetting to record cases would lead to an error in the final, mean data presented here.

3.3.3 VETERINARY SCHOOL CASE RECORDS

Table 3.5 illustrates the total number of cases, percentage Rottweilers, mean ages at onset and presentation and mean body weights from the case records of four Veterinary Schools, Edinburgh, Bristol, Glasgow, Cambridge.

Table 3.6 illustrates the breeds diagnosed with cranial cruciate ligament disease during the periods detailed in table 3.5 at Edinburgh, Cambridge and Bristol.

A total of 898 cases of cranial cruciate ligament rupture, involving 61 breeds (including crossbreds) were recorded by the four veterinary school studied. On average, 25.7% of the cases seen were Rottweilers, but the percentage of Rottweilers seen at individual Veterinary schools ranged from 16.2% at Edinburgh to 30.7% at Glasgow. There were statistically significantly (χ^2 test) more cases of Rottweiler cranial cruciate ligament disease observed than could be expected from their percentage popularity in the general dog population ($p<0.001$).

The mean age of the dogs at the onset of the disease in all breeds seen was 3.9 years (SEM 0.45), the mean age at onset of all the Rottweilers seen was 2.2 years (SEM 0.15). The mean age at presentation of all the breeds seen was 4.1 years (SEM 0.40) and of all the Rottweilers was 2.5 years (SEM 0.11). The mean weight of all the breeds seen was 36.0 kg (SEM 0.81), the mean weight of the Rottweilers was 44.0 kg (SEM 0.54).

Only two cases of cranial cruciate ligament disease in Greyhounds were recorded. One was seen at Edinburgh, the other at Cambridge.

It should be noted that there is an immediate bias in the data examined from the Veterinary Schools because all but Edinburgh run referral-only clinics. Therefore, they will probably see a greater number of large or giant breeds which are, perhaps incorrectly, thought to be more difficult to repair surgically. The large breeds also require hospitalisation/ kennelling facilities unavailable to some smaller general practices.

The data available from the Veterinary Schools was, in some cases, incomplete because, being a retrospective survey, some of the required data had not been recorded. The time periods examined were also uneven due to the data availability and changes in the methods of data storage and recall at the different Veterinary Schools. Finally, only four Veterinary Schools were studied and for the data collated to represent the UK as a whole, it could be assumed that the mean values for the data available are similar to those of the Veterinary Schools which were not examined.

3.4 DISCUSSION

The inherent errors in the data collection methods and in the presented data have been discussed. However, the data base is large and the general practice data was randomly collected from areas throughout the UK. Therefore the breed incidence of cranial cruciate ligament disease reported from the random sample of general practices should reflect the trends in the UK as a whole.

In the two cases of Greyhound cranial cruciate ligament disease, reported from the Veterinary Schools, it was not recorded whether these were Racing or Show Greyhounds.

The breed data from the random survey shows that, between June 1991 and December 1992, 9.4% of all the cases of cranial cruciate ligament disease reported were Rottweilers. This compares with an estimated relative popularity in the general dog population of only 2.7%. In contrast, looking at three of the most popular breeds as determined from the Kennel Club registrations, Labradors, Yorkshire Terriers and Golden Retrievers, there is a close similarity between the relative popularity of these breeds and the proportion of them which presented with cranial cruciate ligament disease in general practice. In the German Shepherd Dog, there were less individuals with the condition than would be expected from the estimated breed popularity.

The data from the Veterinary Schools show the bias of referral clinics discussed previously. The percentage of Rottweilers seen was considerably more (25.7%) and the percentage of Yorkshire Terriers considerably less (0.9%) when compared to the general practice survey. This reflects the tendency to refer and surgically repair the cranial cruciate ligament of larger dogs. The percentage of Rottweilers seen at Edinburgh alone (16.7%), where there is a first opinion clinic, more closely follows the proportion seen in general practice (9.4%).

This study has shown that the general practice survey appears to reflect the incidence of cranial cruciate ligament disease in the general dog population and that there is an over-representation of Rottweilers with cranial cruciate ligament disease in the UK when compared to their breed popularity. There also appears to be an under-representation of German Shepherd Dogs with cranial cruciate ligament disease compared to their breed popularity.

The distinct lack of Greyhounds with cranial cruciate ligament disease, only two out of 1719 cases, shows the rarity of the condition in Greyhounds.

The data indicating the age at onset of clinical signs and at presentation showed that the mean age of Rottweilers was considerably less than that of the general population of canine cranial cruciate ligament disease cases. This was true for both the random survey and the Veterinary School data.

The mean body weights were greater for the Rottweilers alone than for all the dogs together for both data sources. The mean body weight of the Rottweilers determined from the random survey (45.9kg) closely matched the mean weight reported from the Veterinary Schools (44.0kg), but the mean weight of all the breeds was greater for the Veterinary School cases (36.0kg) than the random survey (24.5kg), again reflecting the bias of larger, heavier breeds, including Rottweilers, as opposed to smaller, lighter breeds being referred.

The data collected in this study is in general agreement with that reported by other authors and is summarised in table 3.7.

The percentage of Rottweilers reported with cranial cruciate ligament disease, and illustrated in table 3.7, vary noticeably. In work published prior to 1982 only a few cases were reported in Rottweilers which reflects their lack of popularity in the UK dog population (table 3.1). Between 1984 and 1994 there is an increase in the number of Rottweiler cases reported, which reflects the increasing relative popularity of the breed (table 3.1). It may also illustrate a greater awareness of the chronic, degenerative, possibly partial rupture, often bilateral syndrome seen in larger breeds which may previously have been misdiagnosed.

The percentages of Rottweilers with cranial cruciate ligament disease reported in the UK by Denny and Barr (1984, 1987), Bennett et al (1988), Bennett and May (1991b) and in this study (Veterinary Schools), are all greater than that determined from the random survey in this study. This reflects the bias of second opinion clinics discussed previously.

3.5 CONCLUSIONS

1. Rottweilers, as a breed, are over-represented in the population exhibiting cranial cruciate ligament disease relative to their breed popularity in the United Kingdom.

2. German Shepherd Dogs appear to be under-represented in the population exhibiting cranial cruciate ligament disease relative to their breed popularity in the United Kingdom.

3. The onset of cranial cruciate ligament disease occurs at a younger age in Rottweilers than in the general dog population.

CHAPTER FOUR

ANIMAL LOCOMOTION

"Gaits can be expressed numerically and analysed graphically to reveal their nature and relationship"

M. Hildebrand 1965

4.1 INTRODUCTION

Locomotion can be described as the controlled and deliberate movement of an animal's centre of mass between two locations (Leach 1993). This is achieved by means of gait, a manner of moving the limbs in walking or running and an accustomed, cyclic manner of terrestrial locomotion (Hildebrand 1965, Hildebrand 1977).

Gait analysis of quadrupeds has been studied, in some form, for over 2000 years. Early man depicted gaits on carvings and petroglyphs (Fackelman and Seeherman 1982). Aristotle (384-322 BC) observed the limb movements and coordination in animals (Smith and Ross 1910). A major contribution to gait analysis came from Borelli (1679), who determined the centre of gravity of the body and related it to mammalian movement (cited by Steindler 1953, Sukhanov 1974). The first recorded quantitative gait analysis work was reported by Marey (1873), who used a pneumatic device to record the deformation of India rubber balls attached to the feet of horses during locomotion. Muybridge (1887) pioneered the use of 'moving' pictures to study equine locomotion using a series of 12-24 still cameras, triggered in sequence, to record different gaits used by the horse. Since this early work, numerous researchers have studied quadrupedal locomotion using various recording methods of ever increasing complexity as the technology became available. A detailed summary of the evolution of equine locomotion research has been published by Leach and Dagg (1983a).

4.2 LOCOMOTION BIOMECHANICS

The biomechanics of locomotion studies the relationship between mechanics and biosystems (Badoux 1977) and can be divided into two areas (Leach 1987a); BIOSTATICS - the action of forces on bodies at rest. BIODYNAMICS - motions with reference to masses and forces.

Biodynamics can be further divided into;

BIOKINETICS; The study of forces acting on bodies and the resulting motions.

BIOKINEMATICS; The study of motion without taking into account the forces acting on the subject.

The biomechanical analysis of gait involves a number of kinetic, kinematic and physiological aspects and no one method can accurately collect and collate all the data from these various disciplines (Budsberg et al 1987).

The criteria to be met by the ideal gait analysis system, whether for the examination of the normal or abnormal gait, has been proposed by Leach (1987a). He suggested that the system should;

a, provide accurate, reliable, repeatable and sensitive data.

b, be capable of the refined analysis of high speed locomotion.

c, be mobile, quick and easy to set up and calibrate.

d, have no instruments attached to the subject.

e, be user-friendly and have a large data base for comparison.

f, produce results rapidly and have reasonable operating costs.

g, not alter the movement pattern of the subject.

h, provide enough data to allow diagnostic decisions to be made.

Although this study did not examine the biokinetic aspects of the canine gait and concentrated solely on biokinematic gait data, for completeness, a brief review of the methods available to record the biokinetic data of gait is given.

4.3 METHODS OF BIOKINETIC GAIT ANALYSIS.

4.3.1 FORCE PLATES

These are usually set flush into a walkway and record the magnitude, duration and direction of the external forces resulting from the interaction of the animal with its environment, the ground reaction force (Leach 1993). The ground reaction force consists of three components acting along different perpendicular axes, namely vertical, craniocaudal and mediolateral. Force plate data has been reported for a number of species, *dog* (Barclay 1953, Hutton et al 1969, Roy 1971, Jayes and Alexander 1978, Budsberg et al 1987, Budsberg et al 1988, O'Connor et al 1989, McLaughlin et al 1991, DeCamp et al 1993, Riggs et al 1993), *man* (Cavagna et al 1964, Cavagna et al 1977, Andriacchi 1977, Olney and Winter 1985, Baumann 1986), *horse* (Pratt and O,Connor 1976, Pratt 1977, Pratt and O'Connor 1978, Quddus et al 1978, Schryver et al 1978, Gingerich et al 1979, Gingerich et al 1981, Auer et al 1980, Fackelman and Seeherman 1982, Goodship et al 1983, Leach 1987a, Silver and Rossdale 1983, Merkens 1985, Merkens et al 1988), *cat* (Manter 1938), *goat* (Pandy et al 1988), *sheep* (Barclay 1953, Jayes and Alexander 1978).

Force plates do not describe how the force is distributed over the area of the foot in contact with the ground (Biden et al 1990).

4.3.2 FORCE SHOES

These are advantageous compared to the force plates because they can record data from a number of consecutive gait cycles (Hugelshofer 1982, Ratzlaff et al 1985). However, they require physical attachment to the subject, which may affect the recorded gait patterns.

4.3.3 STRAIN GAUGES

These are attached to bones, tendons or ligaments and they measure the strains on the surface of the tissues during locomotion (Rubin and Lanyon 1982, Bouvier and Hylander 1984).

4.3.4 PEDOBAROGRAPHS

These have been used to study the gaits of cows and pigs. As well as functioning as force plates, they also record the degree of pressure at different points on the sole of the feet during the stance phase of locomotion (Webb and Clark 1981).

4.3.5 ACCELEROMETERS

These are small, lightweight and attached to the trunk or limbs. One type are piezoelectric accelerometers which relay a signal, proportional to the acceleration of the relevant area (Cavagna et al 1964, Morris 1973, Hayes et al 1983).

4.3.6 KAEGI GAIT ANALYSIS SYSTEM

This system is a walkway comprising a number of parallel, fluid-filled sensors attached to a pressure transducer which measures and records the vertical forces only of the stance phase of locomotion (Auer and Butler 1985, O'Callaghan 1991). Like the force shoe, a number of consecutive gait cycles can be measured. Unlike the force plate, the force exerted by different parts of the foot can be determined.

This gait analysis system is rarely used nowadays.

4.4 METHODS OF BIOKINEMATIC GAIT ANALYSIS

4.4.1 PHOTOGRAPHS

A series of still photographs are taken at different stages of the gait cycle and then studied for the footfall patterns and angular joint changes (Marey 1873, Muybridge 1887, Braune and Fischer 1987, Atha 1984).

4.4.2 HIGH SPEED CINEMATOGRAPHY

This method of gait analysis was the natural progression from serial, still photography as the equipment became available and is still the most frequently used method of kinematic gait analysis (Ratzlaff 1988). Detailed descriptions of the methods used in this and previous studies are given in chapter 5. In this and subsequent chapters, the term 'high speed cinematography' refers to the rate at which pictures are taken by the camera and not to the speed of the cinefilm used. A large number of studies have been reported of a wide variety of species using between one and three high speed, 16 millimetre cine-cameras, recording at 32-500 frames per second. The recorded species include *dog* (Hildebrand 1968, Tokuriki 1973a and b, Wentink 1976, Wentink 1977, Charteris et al 1979, Goslow et al 1981, Pratt 1983), *horse* (Hildebrand 1965, Fredricson et al 1970, Fredricson and Drevemo 1972, Fredricson et al 1980, Fredricson et al 1983, Dalin et al 1973, Dalin and Jeffcott 1985, Nilsson 1973, Quddus et al 1978, Ratzlaff et al 1979, Ratzlaff 1988, Drevemo et al 1980a, Drevemo et al 1980b, Fleiss et al 1980, Woltring 1980, Leach and Dagg 1983b, Clayton 1987, 1988, Deuel and Lawrence 1987), *man* (Cavagna et al 1964, Murray et al 1964, Sutherland 1972, Charteris et al 1979, Bauman 1986), *cat* (Manter 1938, Engberg and Lundberg 1969, Goslow et al 1973, Wetzel et al 1975, Carlson-Kuhta and Smith 1990), *rat* (Cohen and Gans 1975, Gruner et al 1980).

4.4.3 VIDEOGRAPHY

Video recording can be considered the modern equivalent of cinefilm recording, with instantaneous playback and long playing tapes. This method has great potential in kinematic gait analysis and will be discussed in comparison to high speed cinematography in chapter 5. Videography, using between one and four video cameras, has been described in a number of species, *dog* (DeCamp et al 1993), *horse* (Peloso et al 1993), *cat* (Pratt and Loeb 1991), *goat* (Pandy et al 1988).

4.4.4 ELECTROGONIOMETRY

There are a number of different forms of electrogoniometer. One measures the joint angle changes during locomotion using a potentiometer positioned at the axis of rotation of each joint (Leach 1987a & b). Joint angle changes are recorded as alterations in the electrical flow through the potentiometer. The potentiometer and the chassis to which it is attached, are together called an electrogonimeter, or elgon. Electrogoniometers have been used to record kinematic data in a number of species, *dog* (Adrian et al 1966), *man* (Karpovitch et al 1960, Tipton and Karpovitch 1965, Kettlekamp et al 1970, Chao 1980, Bober et al 1987), *horse* (Taylor et al 1966, Adrian et al 1977, Ratzlaff et al 1979, Ratzlaff et al 1982). Two and three dimensional elgons are available and they record accurate joint angle data if they are correctly positioned (Biden et al 1990). However, because they are physically attached to the limbs, with lead wires trailing from the limbs, they can interfere with normal gait patterns (Winter et al 1974, Charteris et al 1979, Leach 1987a and b, Biden et al 1990), especially in smaller, untrained species. Electrogoniometers do not record any data relating to gait patterns or temporal parameters.

4.4.5 AUTOMATIC MOTION ANALYSIS SYSTEMS

These systems measure and analyse the angles of one, two, or three dimensional coordinate data (Leach 1987a and b). Passive or active markers are attached to the skin and are therefore subject to skin movement errors (see chapter 5). Passive markers reflect light, active markers require a power supply to individual markers. These systems include CODA-3, Selspot (Woltring 1975, Floss 1983), CoSTEL and they are described more fully elsewhere (Leach 1987a and b). These systems require expensive, immobile recording systems and most cannot be used in natural daylight, requiring reduced or enhanced illumination.

4.5 ELECTROMYOGRAPHY (EMG)

As the result of placing electrodes in the muscle substance, the electrical impulses generated in active muscles as a function of time during the gait cycle can be recorded, these recording are electromyographs. Surface electrodes are available and less invasive but ideally the fur should still be clipped beneath the electrode and more electrical distortion ('noise') is encountered compared to the intramuscular electrodes. It should be remembered that electrical activity in muscles can be generated by passive stretching as well as active contractions (Nunamaker and Blauner 1993).
This technique cannot be categorised into the biokinematic or biokinetic data collecting groups, but it is used in conjunction with high speed cinematography or force plates to help understand the resulting effects of certain muscle activity on body movement. Electromyographs have been recorded in *dog* (Tokuriki 1973a and b, Wentink 1976, Wentink 1977, Goslow et al 1981), *horse* (Wentink 1976), *cat* (Engberg and Lundberg 1969, Carlson-Kuhta and Smith 1990, Pratt and Loeb 1991), *rat* (Gruner et al 1980).

A combination of kinematic, force plate and EMG recordings, to provide an intergrated analysis of gait in man, has been reported (Apkarian et al 1989, Kadaba et al 1989 and others).

Summaries of the methods of biokinetic and biokinematic gait analysis have been published (Fackelman and Seeherman 1982, Dalin and Jeffcott 1985, Leach 1987a).

4.6 GAIT PATTERNS

In quadrupedal animals, numerous gait patterns have been recognised (Hildebrand 1965, Hildebrand 1968) which have evolved to minimise unwanted displacements or energy costs whilst the body is moving from one point to another (Budsberg et al 1987).

The difference between gaits depends primarily on the sequence of footfalls on the ground during locomotion (Rubin and Lanyon 1982). Gaits can be divided initially into two main groups;

SYMMETRICAL GAITS. These are where the footfalls of a pair of feet (fore or hind) are evenly spaced in time. In the dog, this includes walk, trot and pace (Hildebrand 1968). Many more equine gaits have been recognised (Hildebrand 1965) (fig. 4.2 and 4.3).

ASYMMETRICAL GAITS. These are where the footfalls are unevenly spaced in time and include the gallop and canter (Hildebrand 1965). These gait patterns are beyond the scope of this study.

A further subgrouping distinguishes the different footfall sequences seen within the symmetrical gaits;

LATERAL SEQUENCES. These are where a hind footfall is followed by a forefoot on the same side (fig. 4.1). The footfalls exhibit the following pattern; LH, LF, RH, RF, LH, LF, etc......., eg. walk, where F = forefoot and H = hindfoot.

DIAGONAL SEQUENCES. These are where a hind footfall is followed by a fore footfall on the opposite side. LH, RF, RH, LF, LH, RF, etc....., eg. trot.

In addition, LATERAL COUPLETS are where the footfalls of the fore and hind feet on the same side of the body move as a pair. DIAGONAL COUPLETS are where the fore and hind feet on opposite sides act as a pair (Hildebrand 1965) (fig. 4.2).

In quadrupeds at walk, 2, 3 or 4 limbs support the animal at all times and the limbs on one side perform the same movements as on the other side, but half a gait cycle later. The walk has been described as the most efficient and least tiring form of locomotion in the dog (Howell 1965). Regardless of the footfall pattern of the walk, the main metatarsal pad is always placed on the ground first, followed by the digital pads. The digital pads provide the push off from the ground (Charteris et al 1979, Whittick and Simpson 1990).

At trot the body is supported by two contralateral limbs and usually, one forelimb moves in unison with the diagonally opposite hindlimb (fig. 4.3). The forelimbs are free from the ground longer than the hindlimbs to prevent the ipsilateral hindlimb striking the lifting forelimb as it is placed on the ground (Tokuriki 1973b, Sumner-Smith 1993).

Pace (fig. 4.3) is seen in some long limbed dogs and most cats. The limbs of the same side symmetrically support the animal. Some authors report that pace is a less tiring gait than trot (fatigue gait) (Whittick and Simpson 1990), although there are no studies to prove this statement.

The walking and trotting gaits of long limbed dogs (relative to their body length) usually follow a symmetrical, lateral sequence, lateral couplet pattern (Hildebrand

1965, Hildebrand 1968). The gaits of short limbed dogs often exhibit diagonal couplet footfalls.

The generation of rhythmic motion of each limb, the gait, does not rely on upper motor neuron function. Locomotion is generated, and the generations for separate limbs are coupled together, at the spinal cord level. Upper motor neurons control the fine tune motions (Pearson and Duysens 1976, Pratt 1983, Whittick and Simpson 1990).

This study confines itself to the analysis of the canine walking and trotting gaits because they are symmetrical and are the most commonly used gaits by normal dogs.

4.7 KINEMATIC GAIT ANALYSIS TERMINOLOGY

There is no generally accepted standard terminology to define the temporal and spatial parameters measured during gait analysis (Leach et al 1984). Therefore the terms used in this study are explained (Wingfield et al 1993).

GAIT CYCLE. This is the cyclic movement of a limb between successive impacts of the same foot on the ground.

GAIT CYCLE DURATION. This is the time taken to complete one gait cycle.

STRIDE LENGTH. This is the distance the foot moves during one gait cycle relative to the ground.

CADENCE. Cadence is an ambiguous term in mammalian locomotion. In the bipedal movement of man, it is used to describe the number of foot strikes (steps) per minute (Chao 1980). In equine dressage, cadence describes the gait combined with rhythm

(Podhajsky 1967, Ljungquist 1976), and foot strikes per minute is referred to as tempo. Therefore in this study, the term gait cycle frequency will be used to describe the number of gait cycles per minute.

4.8 THE GAIT CYCLE

The gait cycle can be divided into two phases;

Stance phase which is the period when the foot is at zero velocity on the ground. The stance phase comprises two further portions; the beginning of weight-bearing (E_2) and a propulsion or active extension portion (E_3) (Manter 1938) (fig. 4.4 and 4.5).

Swing phase which is the period in the gait cycle when the foot is moving relative to the ground (Wingfield et al 1993) and it is also divided into two portions; a flexion portion (F) and an early extension portion (E_1) (Manter 1938) (fig. 4.4 and 4.5).

At walk, a limb weight-bears (stance phase) for approximately 60 percent (%) of the gait cycle duration. At trot the stance phase duration as a percentage of gait cycle duration falls below 50%.

It is the differences and changes in the relative durations of these subdivisions of the gait cycle and the spatial characteristics of the gait cycle relative to the body conformation, which distinguish different gait and speed patterns in different species and breeds.

4.9 GAIT FORMULA

Using the kinematic data collected from high speed cinefilm, Hildebrand (1965) developed a precise method of describing and contrasting quadrupedal gaits, in the form of a ratio, the **gait formula.**

$$\text{Gait formula} = \frac{\text{\% gait cycle duration that hind foot is on the ground}}{\text{\% gait cycle that forelimb footfall lags behind hindlimb on same side}}$$

Hildebrand (1965, 1968) identified 240 different gait formulae from cinefilm of 37 breeds of dog. He emphasised that the filmed gait should be smooth, at a constant speed over level ground and that the gait formula should be calculated from a minimum of 2-4 consecutive gait cycles. Alexander (1977) stated that any gait can be described by giving two quantities for each foot, a, Relative phase (the fraction of the gait cycle by which the foot in question lags behind the phase of a reference foot (McMahon 1985)). b, Duty factor (the fraction of the gait cycle duration that the foot is on the ground (Alexander 1977)). That is the gait formula described by Hildebrand (1965).

4.10 NORMALISATION OF DATA

Direct comparison of the kinematic gait parameters of a variety of species, breeds and individuals has increased validity following the normalisation of the data to dimensionless parameters to allow for different sized individuals' limb lengths (Jayes and Alexander 1978).

Where u = speed of locomotion g = acceleration due to gravity

h = hip height at rest λ = stride length

Froude number = u^2/gh = a dimensionless speed parameter

Relative stride length = $\bar{\lambda} = \lambda / h$

In normal quadrupedal locomotion, at walk the Froude number is up to 0.5 and the duty factor is greater than 0.5 (Alexander 1977, Alexander 1992). At trot, the Froude number is between 0.5 and 4

At gallop, the Froude number is greater than 4.

As the speed of locomotion increases, the stride length (and relative stride length) increases and the gait cycle duration decreases (Howell 1965, Hildebrand 1966, Gray 1968, Dusek et al 1970, Tokuriki 1973a and b, Cohen and Gans 1975, Alexander 1976, Leach 1993, Ratzlaff 1989). Heglund et al (1974) reported that although the gait cycle frequency increased with increased speed, the stride length remained the same. The reduced gait cycle duration with increased speed of locomotion is mainly due to a decrease, up to 75%, in the E_3 portion of the stance phase (Whittick and Simpson 1990). However, Ratzlaff and Grant (1985) reported that the increase in stride length contributes more to the increase in the speed of the horse than changes in either the swing or stance phase durations.

4.11 BIOKINETICS

Although this study involves only kinematic gait analysis, a brief summary of the kinetic events occuring in the limbs during locomotion, as reported in various studies, is given.

4.11.1 INTERNAL ENERGY

The limbs have two types of energy, gravitational (potential) energy which exists due to the height of the centre of gravity of the limb, and kinetic energy which results from the speed of the centre of gravity. During walking, there is an alternate transfer between potential and kinetic energy which fluctuate out of phase. At walk, the limbs act like a pendulum or stiff strut and there is little or no flexion in the joints, distal to the hip, during the stance phase (Cavagna et al 1977). The centre of gravity is highest as the foot moves vertically beneath the hip joint and therefore the potential energy is most and the kinetic energy least at this point. Because there is little or no joint flexion and muscle lengthening, there is no elastic storage of energy (Goslow et al 1981). During trotting, there is less fluctuation between potential and kinetic energy because, as the result of joint flexion, the vertical displacement of the centre of gravity is less during the stance phase than at walk. The potential energy is low, the kinetic energy is high and because there is joint flexion and muscle lengthening, the limb is spring-like and stores some energy as elastic rather than potential energy. This is converted into kinetic energy to accelerate the limb. The potential and kinetic energies of the limbs can be calculated from cinefilm if the centre of gravity of each segment, height, velocity and segment masses are known (Alexander 1977).

4.11.2 GROUND REACTION FORCE

During weight-bearing, external forces result from the interaction of the dog with its environment, the ground reaction force (Leach 1993). This force comprises component forces in three directions (fig. 4.6), the vertical force, which is the major component and counteracts the pull of gravity on the body (Grillner 1981), the craniocaudal force which is approximately ten times less than the vertical force (Barclay 1953, Hutton et al 1969), and the mediolateral force. The latter force is negligible in normal gaits conducted in a straight line and will not be referred to again. These forces can be measured using a force plate or they can be calculated from the moments about the joint and the length of the muscles from the joint angles.

At walk, the vertical force has two peaks, at trot it has only one (Alexander 1977) (fig. 4.7). The ground reaction force components are usually expressed as a percentage of body weight to allow for the comparison of different sized individuals (Leach and Dagg 1983b).

As the morphometric measurements of the subject increase, the peak vertical force decreases but the total vertical impulse (the total force applied over time) increases (Budsberg et al 1987, Riggs et al 1993). As the velocity of locomotion increases and therefore the stance phase duration decreases, the peak vertical force increases but the vertical impulse decreases (Dueland et al 1977, Leach 1993, Riggs et al 1993). When standing and at walk, about 60% of the total vertical force passes through the forelimbs and 40% through the hindlimbs (Roy 1971, Kimura et al 1979, Budsberg et al 1987). Hutton et al (1969) reported that at walk, this resulted in a vertical force of 110% body weight on the front limbs and 80% body weight on the hind limbs, however Steiss et al (1982) and Budsberg et al (1987) reported vertical forces of 30% body weight on each fore limb and 20% on each hind limb.

The craniocaudal impulses can be divided into braking and propulsion phases. The former is greater in the forelimbs and the latter is greater in the hindlimbs (Budsberg et al 1987) (fig. 4.7).

4.12 CONFORMATION

Conformation can be defined as body shape and form which includes bone length as well as joint angles (Ensminger 1969, Adams 1974). As discussed previously, a number of kinematic gait parameters are linked to the conformation of the subject. The relative stride length (λ/h) and the Froude number (u^2/gh) are related to the hip height at rest (Jayes and Alexander 1978). There is a significant correlation between stride length and limb length. The longer the limb, the longer the stride length, although to contribute to the speed, the limbs must be relatively longer compared to the body length (Hildebrand 1974).

The spine transmits forces between the fore and hind limbs and a variation in the ratio of the spine to limb length will alter the gait of the subject (Roy 1971). The limbs of cursorial animals, including the dog, increase their effective limb length by increasing the metatarsal length (Gray 1968). Because the metatarsus is light compared to the proximal limb due to its lack of muscle bulk, the centre of gravity of the limb is nearer to the centre of rotation of the hind limb, the hip joint. This reduces the work required to flex the limb as the centre of gravity of the limb does not have to be moved so much to lift the distal limb. It also reduces the inertial moment acting on the limb during the swing phase.

In quadrupeds, the hind limbs are less straight than in man and so instead of acting as a truly stable vertical strut, flexion moments act on the joints and the intrinsic muscles of the limbs have to become active to keep the joint angles constant. The strain on the intrinsic muscles depends on the postural joint angles, the weight carried by the limbs and the forces exerted by the extrinsic muscles (Gray 1944). Therefore the straighter the limbs, the less muscle force and work is needed to prevent the limb joints from flexing (Alexander 1991). The ratio of hip height to limb segment length varies. If the ratio is large, the animal walks on relatively straight limbs, if the ratio is small, the limbs are relatively bent (Alexander 1991) (fig. 4.8).

4.12.1 PEAK VERTICAL FORCES AND CONFORMATION

Budsberg et al (1987) demonstrated, using force plates, that there is a negative correlation between the peak vertical forces of the foot per unit of body weight during the stance phase and between the humeral, femoral and paw lengths.

4.12.2 JOINT ANGLE MOVEMENT AND CONFORMATION

The shape of the joint angle versus time curves have been reported to be intrinsic to an animal's limb conformation, gait, health and disease (Draganich et al 1991). Standing angles in the dog have been reported to vary as the result of skeletal dimensions by as much as 20^{o} at the hock, 15^{o} at the stifle and 10^{o} at the hip (Adrian et al 1966).

4.13 DISCUSSION

This chapter has examined the classifications, subdivisions and previous methods of study of quadrupedal locomotion in general, as an introduction to the studies of the canine kinematic gait analysis reported in chapters 5 and 6.

CHAPTER FIVE

HIGH SPEED CINEMATOGRAPHIC CANINE KINEMATIC GAIT ANALYSIS

5.1 INTRODUCTION

In the previous chapter, a number of methods of kinematic gait analysis were discussed briefly.

The population sample of normal Rottweilers and Racing Greyhounds used in this study belonged to members of the general public and the gait recording was carried out at the owners' premises. Therefore the gait analysis technique used in this study had to fulfil certain criteria additional to those suggested for the ideal gait analysis system by Leach (1987a) (chapter 4);

a, the equipment must be mobile and not easily damaged in transit.

b, the method used should be pain-free and not involve any invasive or disfiguring procedures.

The methods available for kinematic gait analysis include (see section 4.4);

5.1.1 ELECTROGONIOMETRY (ELGONS)

Elgons have been used in previous studies of canine gait (Adrian et al 1966) but they are unsuitable for this study for two reasons. Firstly, for the greatest accuracy of measurement of joint angle changes, the fur beneath the potentiometer should be removed to allow the optimum contact between the apparatus and the subject. Secondly, Winter et al (1974), Leach (1987a and b) and Charteris et al (1979) reported that the physical attachment of the apparatus across the joints, with its trailing wires, can interfere with the normal gait patterns of the untrained subject.

5.1.2 AUTOMATIC MOTION ANALYSIS TECHNIQUES

These systems, including CODA3 and Selspot, are prohibitively expensive, immobile and often require artificial lighting (Woltring 1975, Floss 1983, Leach 1987a and b).

5.1.3 VIDEOGRAPHY VERSUS HIGH SPEED CINEMATOGRAPHY

Videography is the most recent technical advance from cinematography for the visual representation of dynamic events. It appears to have great potential in kinematic gait analysis and has been the method of choice in a number of reported studies (Pandy et al 1988, Pratt and Loeb 1991, DeCamp et al 1993, Peloso et al 1993). Videography overcomes some of the major drawbacks to high speed cinematographic gait analysis, namely, immediate playback of the recorded event and the videotape has a long recording time.

Domestic video cameras record at a rate of 50 (Europe) or 60 (USA) fields per second (50 or 60 Hz), but each picture displayed on a video monitor is composed of two interlaced fields, resulting in a frame rate of only 25 or 30 frames per second. To achieve accurate placement of footfalls related to time and thereafter accurate measurements of other kinematic parameters, the number of pictures recorded per second is significant. Generally, the faster the locomotion being recorded, the greater the framing rate required to accurately represent that gait. Capozzo et al (1975) reported that the minimum number of data points needed to describe one gait cycle is 16-20. Therefore, the duration of the gait cycle, and so the speed of the gait, determines the framing rate required.

Hutton et al (1969) reported that a canine walking gait recorded at 24 frames per second was too slow to detect foot placement and lift-off accurately. Subsequent studies have satisfactorily recorded canine locomotion at 50-200 frames per second (Hildebrand 1968, Tokuriki 1973, Wentink 1976, Wentink 1977, Charteris et al 1979, Goslow et al 1981).

Digitised video cassette recorders are available which advance the tapes field by field as opposed to frame by frame, resulting in 50-60 views per second. However, the recorded images are displayed on a video monitor which has a curved tube with a thick glass screen. These properties mean that a ruler cannot be placed directly over the image and significant inaccuracies are likely due to parallax, curvature error and optical distortion (see 5.5, 5.6) (Clayton 1990, Clayton 1991).

A video disc analysis system[a] (1990) is available which uses a video disc instead of a tape and a microprocessor simulates speeds of up to 2082 frames per second on continual playback. However, the system still only records the dynamic events at 50 fields per second. This system is quite expensive to hire and the video disc is liable to damage and dust contamination.

After assessing the methods of videography and high speed cinematography, it was decided to use the latter method in this study.

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[a] 'Sammys' Samuelson Film Services London Ltd, Uxbridge, Middlesex.

5.2 HIGH SPEED CINEMATOGRAPHY

High speed cinematography is still the most frequently used method of recording and measuring the spatial and temporal gait parameters of locomotion (Ratzlaff 1988). There is no standardised technique and methods vary according to the species under investigation, the equipment available and personal preference.

Continuous belt treadmills have been used as the 'walkway' during locomotion recording for a number of species, including the *dog* (Tokuriki 1973, Wentink 1976, Wentink 1977, Goslow et al 1981), *horse* (Fredricson et al 1983, Ratzlaff 1988, Seeherman 1991a and b), *cat* (Stuart 1973, Miller and van der Burg 1973, Wetzel et al 1975, Pratt and Loeb 1991), *rat* (Gruner et al 1980). Opinions as to the influence of treadmills on normal locomotion patterns vary. Fredricson et al (1983) and Seeherman (1991b) reported significantly shorter stride lengths, gait cycle durations and swing phase durations in horses recorded using a treadmill compared to open ground. Wetzel et al (1975) reported a significantly reduced E_1 (early extension) (see 4.8) portion of the swing phase in cats recorded on a treadmill. In contrast, Wentink (1976) and Goslow et al (1981) reported no significant differences in the stance phase, swing phase or gait cycle frequency of dogs walked on a treadmill. It is suggested that the gait of these dogs was unaffected because they were trained to walk on the treadmill. Only one dog was walked on open ground in each study, which makes statistical comparison with treadmill locomotion impossible.

Ray (1979) demonstrated changes in joint angle movements of the limbs of horses on different track surfaces.

A decrease in stride length and gait cycle frequency has been reported in horses traversing sand compared to a firm surface (Dusek et al 1970).

For three dimensional, kinematic gait analysis, usually more than one camera (cine or video) is required to record the limb movements in more than one plane (Andriacchi 1977, Clayton 1991, DeCamp et al 1993).

For more simplified two dimensional analysis, only one camera is necessary. Ideally the optical axis should be normal (at right angles) to the plane of movement of the subject (Dalin and Jeffcott 1985, Yeadon 1990).

Previous studies using one cinecamera have recorded locomotion by one of four methods;

a, One camera is mounted on a fixed tripod and is directed at the side of the animal walking on a treadmill to record a sagittal view of the movement of the subject. The optical axis of the camera is always normal to the direction of motion.

b, One camera is mounted on a fixed tripod and the subject moves on open ground across the field of view. The width of the field view depends on the type of lens used and the distance from the camera to the subject. Often, the size of the image is sacrificed to increase the field of view and therefore increase the number of consecutive gait cycles recorded. Only the central gait cycle is truly normal to the optical axis and many authors just measure the gait parameters of one gait cycle during each locomotion (Nilsson 1973, Deuel and Lawrence 1987).

c, One camera is mounted on a tripod capable of rotating around the vertical axis. As the subject moves in a straight line, the camera follows the movement by panning, keeping the whole subject in the field of view. This allows the subject's image to be larger than when using the fixed camera, but it introduces a perspective error, which is the result of changes in obliquity of the subject relative to the optical axis of the camera (Hyzer 1962, Clayton 1991). The direction of movement is not normal to the optical axis of the camera throughout the locomotion. Goslow et al (1973) trained cats to move, by means of a barrier, parallel to and in front of, a bowed board, whilst panning a camera to follow the locomotion. The direction of movement was therefore normal to the optical axis throughout. They stated that *"this restriction did not appear to alter the normal movement of the cats"* but they produced no data to support this statement or to show whether the curved walkway affected the gait kinematics due to changes in the forces exerted on and by the limbs.

d, Moving one camera parallel to the direction of locomotion and at the same speed. The optical axis of the camera remains normal to the movement of the subject at all times. This method has been reported by a number of authors (Fredricson and Drevemo 1972, Fredricson et al 1983, Olney and Winter 1985, Bauman 1986).

OPTICAL ERRORS

There are two main sources of error associated with the photographic techniques;

STATIC ERROR which involves optical distortion (including perspective error) and parallax

DYNAMIC ERROR which involves image blur (Hyzer 1962).

Parallax error relates to the relative magnification of the limb closer to the camera compared to the opposite limb (Clayton 1991). Both parallax and optical distortion are reduced by siting the camera as far as possible from the subject without compromising the image size too much (Hyzer 1962, Charteris et al 1979). Constructing a measured grid behind the subject and recording a still picture of a measuring stick in the same plane as the stationary animal prior to filming, allows correction for any parallax and optical distortion which may be unavoidable (Olney and Winter 1985).

The amount of image blur depends on the speed of the subject, the duration of the frame exposure and the image magnification (image size divided by the object size) (Clayton 1991). Ideally, the frame exposure time should be short so there is only a small amount of object movement when the shutter is open. The faster the speed of locomotion, the greater the framing rate and the shorter the frame exposure duration is required. For example, in walking man, Bauman (1986) used 50-100 frames per second and a frame exposure of 1/500 second. In the galloping horse, Deuel and Lawrence (1987) used 243 frames per second at a frame exposure of 1/2190 second to record horses galloping at 13.1m/s.

To make accurate linear and angular measurements, parallax, optical distortion and image blur should be minimised (Clayton 1991).

The framing rates of high speed cinematography have been verified by filming a stop watch and counting the number of frames exposed over a certain period of time (Pratt 1983), or with camera-interval timing lights (Carlson-Kuhta and Smith 1990).

To measure the changes in spatial parameters, relative to time, of limb segments and joint angles during locomotion, certain points on the limbs must be visualised with markers prior to filming. Although bone-implanted light emitting diodes (LED) and transcutaneous pins have been used experimentally (van Weeren and Barneveld 1986, van Weeren 1989), the most commonly used, repeatable and non-invasive method of identifying positions on the limbs is to mark the skin using bony prominences as landmarks which can be visualised or palpated consistently in individual animals. There are no universally recognised standard placement positions for these markers, and because of the numerous studies of high speed cinematographic gait analysis, a number of combinations of sites have been reported. The skin markers on the distal limb and over the hip joint have invariably been positioned over the lateral (fibular) malleolus, the distal 5th metatarsal bone and the proximal greater trochanter of the femur (Adrian et al 1966, Olney and Winter 1985, Mann et al 1988, van Weeren 1990a and b, Pratt and Loeb 1991, DeCamp et al 1993). The lateral femoral epicondyle (Schmaltz 1906, Adrian et al 1966, Wentink 1976, Deuel 1985, Olney and Winter 1985, Mann et al 1988), mid-point between the lateral femoral epicondyle and the fibular head (DeCamp et al 1993), proximal lateral collateral ligament (Magnusson 1985), mid lateral collateral ligament (Leach and Cymbaluk 1986), tibial crest (Langlois et al 1978, Charteris et al 1979, Kobluk et al 1989) have all been used to represent the stifle joint. van Weeren (1990a and b) marked both the lateral femoral epicondyle and the fibular head. The pelvic markers have varied from the iliac crest (DeCamp et al 1993), tuber coxae (van Weeren 1990a and b), dorsal ischiatic tuberosity and the dorsal ischiatic spine (Mann et al 1988), the ischiatic tuberosity and the wing of the ilium (Adrian et al 1966).

Ideally, the skin markers should be placed over the instant centres of rotation of the joints (Clayton 1991) which may vary from species to species, especially at the stifle joint (Ireland et al 1986, Leach and Dyson 1988). The position of the instant centres of motion of the stifle joint alters with flexion and extension (see chapter 1), so wherever the stifle joint marker is originally positioned, it will not remain over the instant centre of rotation throughout the gait cycle.

There is little variation in spatial and temporal gait parameters between successive gait cycles during normal locomotion at a constant speed over level ground, but measurement of a minimum of 3-5 consecutive gait cycles has been reported to accurately represent the kinematic gait parameters of individual subjects (Hildebrand 1965, Hildebrand 1968, Fredricson and Drevemo 1972, Drevemo et al 1980a). The beginning and end of a period of locomotion do not represent average gait cycles and should not be included in the gait analysis, especially as the speed of locomotion increases (Leach and Cymbaluk 1986, Wingfield et al 1993).

There have been no reported studies comparing the kinematic symmetry between the left and right limb pairs in individual dogs, but Budsberg et al (1993) reported no statistically significant difference between the left and right side force plate data in individual dogs.

Jevens et al (1993) reported that up to 7% of the variation between the force plate data of different dogs and different locomotion periods was due to the handler.

The effect of training on locomotor patterns is not fully understood (Leach and Dagg 1983b) but Drevemo et al (1980a) and Leach and Sprigings (1979, 1980) reported that, compared to untrained horses, trained animals had increased stride lengths and increased gait cycle durations due to an increased swing time.

ERRORS IN HIGH SPEED CINEMATOGRAPHIC GAIT ANALYSIS

Two types of error are recognised in high speed cinematographic gait analysis;

a, RANDOM ERRORS which can be present or absent to different levels on a frame to frame basis. Errors include film blur, image shrinkage and optical distortion (Fredricson and Drevemo 1972, Gruner et al 1980). Methods of minimising these errors have been discussed.

b, SYSTEMATIC ERRORS are consistent from frame to frame and include 3 main error groups;

1, Limb movement out of the vertical plane. If a two dimensional, sagittal film is recorded, internal and external rotation, of the limb as a whole, will decrease the apparent flexion of the stifle joint. However, the pattern of motion, independent of the absolute values, will be unaffected (Gruner et al 1980, Biden et al 1990).

2, Malpositioning of joint skin markers (Wentink 1976, Gruner et al 1980, Biden et al 1990, DeCamp et al 1993). If the skin markers are not placed correctly over the bony landmarks, the movement of these markers will not represent the true joint angle changes of the limbs. Malpositioning may result from either correctly positioning the marker but over the wrong bony prominence, or incorrectly positioning the marker over the correct bony prominence. Minor misplacements will result in a shift of the joint angle/time curves either up or down on the Y axis but the curve shape is unaffected (Kadaba et al 1989).

3, Movement of skin over the bony landmark. This is probably the most difficult error to minimise (Wentink 1976, Gruner et al 1980, van Weeren and Barneveld 1986, van Weeren 1989, van den Bogert et al 1990, Clayton 1991). Skin is mobile and will stretch, slacken or contract during locomotion due to muscle contraction, gravity etc. Studies have been done experimentally to quantify and correct for skin movement in equine locomotion using highly invasive light emitting diodes and transcutaneous pins (van Weeren and Barneveld 1986, van Weeren et al 1988, van Weeren 1989, van den Bogert et al 1990). They found skin movement, in the equine, of up to 39 millimetres over the distal tibia due to craniodorsal movement over the circumference of the bone. Some studies reported that subjectively, there is little movement over the greater trochanter in dogs (Wentink 1976), whereas others report significant skin movement (Charteris et al 1979) but no quantitative work has been done. In some studies, fur has been shaved off over the bony prominences to reduce the likelihood of fur movement compounding the effects of skin movement (Gruner et al 1980, Deuel 1985).

To correct for skin movement, some authors have reported the use, in equines, of a correction algorithm on a linear regression model of skin displacement using the digitisation of the two dimensional X-Y co-ordinates of the skin markers (van Weeren et al 1988, van den Bogert et al 1990). Other studies have corrected for skin movement at the stifle joint by using the skin markers at the greater trochanter and lateral malleolus, where subjectively there is only minor skin movement, and calculating the stifle angle at each time point during the gait cycle trigonometrically from the cinefilm recordings (Goslow et al 1973, Goslow et al 1981, Pratt and Loeb 1991).

Similar skin movement can be expected when comparing members of the same species with similar conformation (van Weeren and Barneveld 1986).

Although the amount of accumulated error has been reported to sometimes be more than 10 percent, the amount of error in the measured compared to the actual values of the joint angle changes during the gait cycle can be qualitatively assessed from the angle/time plots. Large random errors are exhibited as sudden changes in joint angles on the plot instead of a smooth curve.

Previous studies of canine hindlimb joint angle changes at walk and trot are in general agreement (Adrian et al 1966, Goslow et al 1981, DeCamp et al 1993). At walk, during the stance phase, the hip joint extends, the stifle joint angle changes very little and the hock joint initially extends, flexes in mid-stance and then extends prior to the start of the swing phase. During the swing phase, the hip joint flexes and the stifle and hock joints flex and then extend prior to foot placement.

At trot, during the stance phase, the hip extends, the stifle joint extends, flexes and then extends again, the hock joint extends and then flexes. During the swing phase, the hip flexes and both the stifle and hock joints extend, flex and finally extend prior to foot placement.

In the above context, mid-stance refers to the position of the limb in the stance phase, and not the middle of the stance phase duration period.

The motion of the hind limb joint angles are similar at walk and trot, but they are more exaggerated at trot (Biden et al 1990).

There have been no previous studies comparing the kinematic gait parameters of different breeds of dog in detail.

AIMS OF THE HIGH SPEED CINEMATOGRAPHIC KINEMATIC GAIT ANALYSIS

The aims of this section of the study was to film, record, analyse and compare, in two dimensions in the sagittal plane, the kinematic gait parameters of the normal walking and trotting gaits of both the left and right hind limbs of two breeds of dog, namely Rottweilers and Racing Greyhounds, using high speed cinematography.

5.3 MATERIALS

A total of 28 Rottweilers and 28 Racing Greyhounds, belonging to the general public, were filmed. These included 25 mature (1-3 years old) (44% male and 56% female) and 3 immature (6-8 months old) (67% male and 33% female) Rottweilers and 25 mature (52% male and 48% female) and 3 immature (67% male and 33% female) Racing Greyhounds. The mean ages of the mature Rottweilers and Racing Greyhounds were 23.7 months (1.87 months standard error of mean SEM) and 26.0 months (SEM 1.82 months) respectively. The mean ages of the immature Rottweilers and Racing Greyhounds were both 8 months (SEM 0.00).

None of the dogs had a history of previous hindlimb lameness and no abnormalities were detected on clinical examination.

5.4 DISTRIBUTION OF BODY MASS

The approximate percentage distribution of body mass transmitted through the fore and hind limbs of the dogs standing normally was measured. The dogs were positioned centrally on a solid plank of wood so that the distances from the feet to the scales are equal (front and rear) and small. The plank was supported symmetrically at each end by a mechanical weighing machine (fig 5.1). The sum of the masses recorded at both the fore (m_f) and hind (m_h) ends was the total body mass (m_t) of the dog.

$$m_f + m_h = m_t$$

$$\frac{m_f}{m_t} \times 100 = \text{percentage body mass supported by the forelimbs}$$

$$\frac{m_h}{m_t} \times 100 = \text{percentage body mass supported by the hindlimbs}$$

5.5 SUBJECT PREPARATION

The dogs were filmed using a 16 millimetre (mm) Paillard-Bolex H16 Reflex cinecamera with a 50mm focal length lens and the mechanical shutter 1/4 open. The camera was loaded with 100 foot spools of Eastman Ektachrome High Speed daylight film 7251, ISO 400, ASA 64.

Standing morphometric and joint angle values were measured from still frame pictures taken by the cinecamera, as it proved impossible to keep the dogs stationary whilst the measurements were taken manually. A measured pole was positioned in the same plane as the dog to allow correction of the film image measurements to the actual linear measurements (parallax errors).

Eight millimetre diameter, self-adhesive paper circles were positioned on the unshaven skin over certain bony prominences of the hind limbs to indicate the changes in the position of these prominences during the gait cycle. The positions of the bony prominences underlying the skin markers are illustrated in fig 5.2. They were; cranial dorsal iliac spine, ischiatic tuberosity, proximal greater trochanter, lateral femoral epicondyle, lateral (fibular) malleolus, distal lateral metatarsus, distal 2nd phalanx of the 5th digit. An adhesive marker was also placed over the greater tubercle of the humerus, to allow the measurement of the body length.

The joint angles measured, both in the standing and moving dog are illustrated in fig 5.2 and fig 5.3.

The skin markers of the hip, stifle and hock joints were placed over the approximate positions of the instant centres of rotation of the joints. Although the instant centres of rotation of the stifle joint moves cranial and caudal during flexion and extension (chapter 1), the marked position is at the mean instant centre of rotation in the dog, at the attachment of the lateral collateral ligament to the femoral epicondyle (Ireland et al 1986). Lines joining the instant centres of motion of the hip, stifle and hock joints represent the functional axes of the femur and tibia.

5.6 FILMING PROCEDURE

A treadmill was not used in this study because; they are not mobile, it was not possible to train the dogs to use the treadmill which may affect their gait patterns (Fredricson et al 1983, Wetzel et al 1985, Seeherman 1991a and b), and a further kinematic gait analysis system 'Gaitway'), described in chapter 6 and by Law (1987) and Wingfield et al (1993), used to complement the cinefilm analysis, requires the dog to move forward relative to the stationary ground.

To choose a method of filming canine locomotion over open ground, a 540 centimetre (cm) long grid of horizontal and vertical poles with markers every 5cm was set up behind, but parallel to, the plane of motion. Lengths of adhesive tape, 50cm apart, were placed on the ground at right angles to the direction of motion (fig 5.4).

5.6.1 FIXED FIELD

The fixed field of view method was discarded because only two consecutive walking gait cycles were visible at a subject to camera distance where the dog image was sufficiently large to readily appreciate the skin markers. The camera to subject distance was also restricted by the limited space available at the premises of the dogs' owners.

5.6.2 PANNING

The cinecamera was positioned on a tripod, half way along and 1000cm from the walkway. The camera was manually, axially rotated to follow the progress of the dog along the walkway.

5.6.3 MOVING CINECAMERA

A trolley was designed to move the camera smoothly, parallel to the dog's direction of motion. The trolley had four (4) wheels, the two (2) nearest the walkway had rubber tyres, the opposite side had a pair of grooved wheels which fitted over a 720cm long wooden pole running parallel to the direction of locomotion of the dog (fig 5.5). The single pole acted as a rail to guide the trolley plus cinecamera, and kept the camera to object distance constant. The tripod was expanded so that all three legs were horizontal, at 120 degrees to each other in the same plane, and the camera lens was approximately level with the stifle joint of the standing dog. One leg of the tripod was aligned along the optical axis of the camera to act as a guide to visually orientate the camera without the operator having to constantly look down the view-finder (fig 5.5). The trolley was manually propelled along the rail at the same velocity as the dog.

To compare the panning and moving camera methods, one Racing Greyhound was recorded twice walking in a straight line, 1000cm from the camera, once panning the camera, and once using the trolley. The apparent distance between the equidistant (50 centimetres, cm) adhesive ground tapes and their apparent angle relative to a vertical line, superimposed on the film frame, were measured along the length of the walkway (fig 5.4). Marked lengths (x = 15cm) on the horizontal poles of the background grid were also measured every 50cm along the walkway. Finally, the angle between the greater trochanter, the lateral femoral epicondyle, and the lateral malleolus skin markers were measured from each frame for 5 consecutive gait cycles. The measured values of the panning and trolley methods were compared, to assess the amount of optical distortion error of the images in the two methods.

The method of choice was to use the trolley to follow the dog at the same velocity.

5.7 HIGH SPEED CINECAMERA FRAMING RATE

A framing rate of 64 frames per second was selected on the cinecamera. This frame rate was checked by filming a digital stopwatch for 3-4 seconds and manually counting the number of frames exposed during that time.

The framing rate was re-checked every time the film spool was changed, which was every second dog filmed.

The Rottweilers were filmed at one of two premises and the Racing Greyhounds at one of three.

Attempts were made to standardise the recording conditions as much as possible. All the dogs were recorded walking and trotting over hard, level ground, either tarmacadam or concrete, as the ground conditions can affect the gait parameters during locomotion (Dusek et al 1970, Ray 1979).

The camera to subject distance was between 9000cm and 1100cm for all the recordings. Different handlers were used to walk the dogs, but Jevens et al (1993) reported that only 0-7% of the variance between individual dogs and different locomotions of the same dog were due to the handler. Similar walking and trotting speeds for each dog of both breeds were achieved by allowing approximately the same time for the dogs to complete the 540cm walkway. Both left and right hindlimbs for each dog were recorded at walk and trot.

The beginning and end of each walk or trot were beyond the grid area and were not recorded, as the initial acceleration and final deceleration gait cycles of a period of locomotion are not representative of the normal gait pattern of the dog (Leach and Cymbaluk 1986, Wingfield et al 1993).

5.8 MEASUREMENT METHODS

Two methods of obtaining measurements from the exposed cinefilm were available;

a, the projection of each frame onto a screen, using a slide projector modified to hold 16mm cinefilm, and manually measuring the gait parameters.

b, using a Videoplan Image Analyser[b] which digitises the position of each skin marker using a freely moveable, light emitting diode cursor which transmits high precision, parallax-free digitised data to a microcomputer to an accuracy of 0.1mm. The correct software will measure the angle between three points, and, using a specific scaling program to calibrate the microcomputer relative to the measured pole in the image, it will measure the true distance between two points.

The two methods were examined for comparable accuracy by measuring the same gait cycles for the same animal with both systems. The repeatability of the Videoplan system was also examined by measuring the same gait cycles, by the same method, on different days.

Prior to detailed frame by frame analysis of the cinefilms, the quality of the recordings were assessed using a hand operated film editing machine[c]. The films were run through the viewer at a slow speed and the gait cycles to be examined in detail were chosen. The speed of locomotion was measured by counting the number of frames taken for the animal to move across the grid's 540cm.

$$\text{Speed of motion} = \frac{540 \text{ centimetres}}{(\text{number of frames} \times \text{duration of one frame})}$$

[b] Kontron Bildanalyse MOP Videoplan

[c] Muray, Paris

5.9 STATIC MORPHOMETRIC AND JOINT ANGLE VALUES

The morphometric values measured from the still frames taken by the cinecamera, on both the left and right sides were (fig 5.6); functional femoral length (f), functional tibial length (t), functional metatarsal length (m), paw length (p), hip height (h), functional limb length (l) (greater trochanter to the distal 2nd phalynx of the 5th metatarsus). A marker was also placed over the shoulder joint to allow the measurement of the body length (shoulder to greater trochanter). The term functional femoral and tibial lengths refers to the distance between the instant centres of rotation of the hip and stifle joints, and the stifle and hock joints respectively and not to the anatomical lengths of each bone. It is not possible to accurately measure the anatomical length of the femur and tibia *in vivo* without the aid of imaging apparatus, as the proximal and distal ends of these bones are not palpable externally.

The joint angles measured were (fig 5.2 and fig 5.3); pelvic (A), hip (B), stifle (C), hock (D), metatarsophalangeal (E), protraction/retraction (pace angle) (F).

Protraction refers to the angle a line from the greater trochanter to the 5th digit makes cranial to the vertical line from the greater trochanter to the ground.

Retraction refers to the angle the same line makes caudal to the vertical line from the hip (fig 5.3).

The sum of the maximum protraction and retraction = pace angle (Gambaryan 1974).

5.10 TEMPORAL AND SPATIAL PARAMETERS MEASURED DURING LOCOMOTION.

The following temporal and spatial parameters were measured from each frame of the cinefilm for 3-4 consecutive gait cycles for each period of recorded locomotion.

TEMPORAL; speed of gait (metres per second, m/s), stride length (metres, m), gait cycle duration (seconds, s), swing and stance phase durations (seconds, s), footfall (gait) patterns and gait formulae.

SPATIAL; pelvic, hip, stifle, hock, metatarsophalangeal and protraction/retraction (pace) angles (degrees). Also the distance between the greater trochanter and the lateral malleolus skin markers (centimetres, cm).

This section of the study was, in part, to determine and compare joint angle changes of the hindlimbs of the Rottweiler and the Racing Greyhound during the gait cycle. The actual joint angle values, especially the maximum joint flexions and extensions, were of interest as well as the range of joint movement.

5.11 TRIGONOMETRIC DETERMINATION OF STIFLE JOINT ANGLES

Errors due to skin movement over bony prominences have been discussed previously (see 5.5.1). Although no quantitative studies have been done in the dog, skin movement at the stifle joint is reported to be significant whereas it is less so at the hip and hock joints (Goslow et al 1973, Wentink 1976, Goslow et al 1981). The stifle joint angle can be calculated by trigonometry (Goslow et al 1973). If the length of the femur (f), tibia (t) and the distance between the greater trochanter and lateral malleolus (s) are known, the stifle joint angle can be calculated (fig 5.7).

$$\cos a = \frac{s^2 + (f^2 - t^2)}{2sf}$$

$$\sin b = \frac{s \times \sin a}{t} \quad \text{where } b = \text{stifle joint angle}$$

The results of direct measurement of the angles between the greater trochanter, lateral femoral epicondyle and lateral malleolus skin markers were compared with the trigonometrically calculated values.

The cinefilms were deliberately slightly under-exposed as this resulted in easier film reading.

5.12 RESULTS

The tables in this section illustrate the mean values of the various parameters measured, but the statistical analyses (t test) were carried out on the values for each individual recorded.

5.12.1 BODY MASS AND DISTRIBUTION

The mean total body masses (kilogrammes kg) and the mean percentages (%) of the body mass supported by the fore and hind limbs of the stationary Rottweilers and Racing Greyhounds, mature and immature, are shown in table 5.1.

The mean total body masses of the immature dogs of both breeds (Rottweilers 37.3kg (SEM 5.2kg) and Racing Greyhound 25.7kg (SEM 3.2kg)) were noticeably lower compared to the mature dogs of the same breed (Rottweiler 42.6kg (SEM 1.2kg) and Racing Greyhound 30.5kg (SEM 0.7kg)). The Racing Greyhounds, both mature (30.5kg (SEM 0.7kg)) and immature (25.7 (SEM 3.2kg)), had lower mean body masses compared to the mature (42.6kg (SEM 1.22kg)) and immature (37.3kg (SEM 5.2kg)) Rottweilers. The forelimbs of both breeds (mature Rottweiler 58.7% (SEM 0.9%), Racing Greyhound 57.6% (SEM 0.8%) and immature Rottweiler 59.0% (SEM 3.6%), Racing Greyhound 59.3% (SEM 2.9%)) carried a greater percentage of the total body mass than the hindlimbs (mature Rottweiler 41.2% (SEM 0.9%), Racing Greyhound 42.2% (SEM 0.96%) and immature Rottweiler 41.0% (SEM 3.6%), Racing Greyhound 40.7% (SEM 2.9%)). There was no statistically significant difference between the mean percentage of the body mass carried by the forelimbs of the mature Rottweiler compared to the mean percentage carried by the forelimbs of the mature Racing Greyhound. The same was true for the hindlimbs of each breed. There was also no noticeable difference between the mean percentage of body mass carried by the forelimbs of the immature compared to the mature dogs of the same breed.

5.12.2 FRAMING RATE

Despite the camera setting of 64 frames per second (fps), the mean framing rate, calculated from counting the stopwatch images, was 50.1fps (SEM 0.2fps) (n = 24) (see section 5.7 page 113).

As the adjustable shutter was one quarter open during all the filming sessions, at a framing rate of 50fps, this resulted in a frame exposure time of 1/100 second (Hyzer 1962), which is comparable with that used in other studies (Bauman 1986).

The dynamic random error of image blur, resulting from the movement of the dogs, and the vertical displacements of the camera whilst the camera shutter was open, was minimal, because the frame exposure time was short and the speed of the dogs at walk and trot was relatively slow.

5.12.3 PANNING VERSUS TROLLEY CINEMATOGRAPHIC RECORDING METHODS.

5.12.3.1 COMPARISON OF LINEAR PARAMETERS

A Racing Greyhound was recorded, using the panning and trolley methods, the measured walking speeds, during the two tests, being 1.05 metres per second (m/s) and 1.10m/s respectively.

The apparent distance between the evenly-spaced ground marker tapes and their apparent angle, relative to a vertical line superimposed on the frame, along the length of the walkway for both methods are illustrated in fig 5.8 and fig 5.9. Fig 5.8 shows the decreasing distance between the ground tapes at the beginning and end of the walkway compared to the middle, in the panned record. The range of the recorded distance between the ground tapes in the panned recording was 48.5 centimetres (cm) to 59.4cm representing the same, true distance of 50.0cm between each tape. The trolley method shows no such fluctuation along the length of the walkway and the range of values representing the tape to tape distance was from 57.6cm to 59.1cm. The values measured from the cineflim are greater than the actual inter-tape distance (50cm), due to parallax error as the ground tapes were in front of the plane of the measuring stick used to calibrate the Videoplan analysis system.

Fig 5.9 shows the increasing angle, relative to the vertical, of the ground tapes at the beginning and end of the walkway using the panning method. There is very little change in the angle of the tape to the vertical along the walkway using the trolley method. The panning method showed a range of angular deviation from the vertical of -67.6 degrees (^{o}) to +71.7 degrees (^{o}) from beginning to end. The trolley method showed a deviation of only -10.7^{o} to +9.4^{o}.

Fig 5.10 shows the measured values of a known, equidistant length (x) of the horizontal poles of the background grid at 50cm intervals along its 540cm length. The same fluctuation of the values, as a function of the distance along the walkway, using the panning method were seen as with the ground tapes in fig 5.8. The panning method showed a range of measured values from 12.8cm to 16.1cm along the length of the walkway, representing the true, equidistant values of 15cm of the horizontal pole. The values measured from the trolley-recorded method vary very little along the course of the walkway (15.6cm to 16.1cm).

5.12.3.2 COMPARISON OF ANGULAR PARAMETERS

The changes in the stifle joint angle during 5 consecutive gait cycles are shown in fig 5.11 for both the panning and trolley methods. To compare adequately the gait cycles of two separate periods of locomotion, the stifle joint angles are plotted against the percentage of the gait cycle duration rather than absolute time, as the durations of each gait cycle are not identical.

The maximum flexion, maximum extension and amplitude of the range of stifle joint motion for each gait cycle and the mean values for the five gait cycles recorded using the panning method or the trolley are given in table 5.2.

Although these values were measured from different walking periods of the same dog, the symmetry in consecutive gait cycles and the repeatability of the gait cycles for individual dogs during different walks at the same speed make comparison of the stifle joint fluctuations during the gait cycles valid.

The mean maximum flexions of the panning and trolley methods were 119.0 degrees (^{o}) (SEM 2.7^{o}) and 118.1^{o} (SEM 0.7^{o}) respectively, the mean maximum extensions were 159.7^{o} (SEM 1.3^{o}) and 159.5^{o} (SEM 0.8^{o}) respectively and the mean ranges of motion of the stifle joint were 40.7^{o} (SEM 1.5^{o}) and 41.4^{o} (SEM 1.3^{o}) respectively. There were no statistically significant differences between the measured maximum flexion angles of the Racing Greyhound when recorded by panning or using the trolley nor between the measured maximum extension angles and the ranges of motion recorded by the two different methods.

5.12.4 ACCURACY AND REPEATABILITY OF METHODS OF HIGH SPEED CINEFILM ANALYSIS

Videoplan image analyser versus manual measurement

The changes in the stifle joint angle of one Rottweiler and one Racing Greyhound, comparing the Videoplan image analysis and manual methods, measuring the same gait cycle in each dog are illustrated in fig 5.12 and fig 5.13. The plots of the stifle joint angle versus frame number for both breeds show the comparable accuracy between the two methods, with little difference between the measured values of the stifle joint in the same frame using the different methods.

Videoplan - measurement repeatability

The repeatability of measuring the same stifle joint angle changes during the gait cycle on different days using the Videoplan image analyser is illustrated in fig 5.14. The plot of the stifle joint angle versus frame number shows that the values measured on one day closely resemble those measured on a subsequent day.

Because there was little difference in the accuracy of the measurement of the stifle angles and the greater ease and speed of use of the Videoplan image analysis system, this was the method used for the analysis of the high speed cinefilm in this study.

5.12.5 STATIC MORPHOMETRIC MEASUREMENTS

The mean morphometric values of the left, right and both sides combined, of the standing mature and immature, Rottweilers and Racing Greyhounds are shown in table 5.3 and table 5.4.

There were no statistically significant differences (two-sample t test) between the mean morphometric values of the left and right sides of the mature animals of the same breed.

MATURE DOGS (table 5.3)

The mean Rottweiler femoral length, of both left and right hindlimbs combined was 20.6cm (SEM 0.6cm) and the mean value for the Racing Greyhound was 20.0cm (SEM 0.3cm), they were not statistically significantly different. The difference between the mean combined tibial lengths of the mature Rottweiler (21.7cm (SEM 0.3cm)) and the Racing Greyhound (25.3cm (SEM 0.4cm)) were statistically significantly different [a]($p< 0.0001$). The mean combined length of the Rottweiler metatarsus was statistically significantly less [b] ($p<0.0001$) than the Racing Greyhound metatarsus. There was no statistically significant difference between the mean combined Rottweiler and Racing Greyhound paw lengths.

The mean combined Rottweiler hip height (the vertical distance from the greater trochanter to the ground) (53.4cm (SEM 0.7cm)) was statistically significantly less [c] ($p<0.0001$) than the mean combined Racing Greyhound hip height (58.9cm (SEM 0.6cm)). The mean combined Rottweiler limb length (greater trochanter to the fifth digit) (53.6cm (SEM 0.8cm)) was statistically significantly less [d] ($p<0.0001$) than the Racing Greyhound mean value (58.2cm (SEM 0.6cm)). The mean combined body length of the Rottweiler was statistically significantly less [e] ($p<0.05$) than the Racing Greyhound.

IMMATURE DOGS (table 5.4)

Because so few individual immature animals were examined (3 Rottweilers and 3 Racing Greyhounds) it would be inappropriate to statistically analyse their results. Therefore only the trends in the figures will be discussed.

The mean femoral, metatarsal and paw lengths of the Rottweiler were similar to those in the Racing Greyhound. The mean Rottweiler tibial length (20.1cm) was noticeably shorter than the Racing Greyhound (24.5cm). The mean hip height of the Rottweiler was less than the Racing Greyhound. The mean Rottweiler leg length (49.5cm) was noticeably shorter than the Racing Greyhound (56.5cm). The mean Rottweiler body length was shorter than the Racing Greyhound.

MATURE VERSUS IMMATURE

Comparing the values of the mature (n = 25) to the immature (n = 3) animals of each breed, as would be expected, the mean hip height, limb length and body length of the mature animals were greater than those of the immature animals of the same breed.

The mean dimensionless ratios (+ SD and SEM) of certain morphometric values in the Rottweiler and Racing Greyhound, including; tibial length/femoral length, femoral length/metatarsal length, hip height/femoral length, hip height/tibial length and body length/limb length are shown in table 5.5.

The mean tibia/femur length ratio of the mature Rottweiler (1.0 (SEM 0.03)) was statistically significantly lower [a] ($p<0.0001$) than the mature Racing Greyhound (1.3 (SEM 0.02)). The mean tibia/femur length ratio of the immature Rottweiler was also noticeably lower than the immature Racing Greyhound. The mean femur/metatarsus length ratio of the mature Rottweiler was statistically significantly greater [b] ($p<0.0001$) than the mature Racing Greyhound. The mean femur/metatarsus ratio in the immature Rottweilers and Racing Greyhounds were the same (1.6).

The mean hip height/femur length ratio was statistically significantly lower [c] ($p<0.0001$) in the mature Rottweiler (2.6 (SEM 0.05)) than the mature Racing Greyhound (3.0 (SEM 0.05)). The means of the immature Rottweiler and Racing Greyhound dogs were also noticeably different. The ratio of the hip height/tibia length was statistically sigificantly greater [d] ($p<0.05$) in the mature Rottweiler than the Racing Greyhound. The mean hip height/tibia length ratios were similar in the immature Rottweiler and Racing Greyhound. The mean body length/limb length ratios were not statistically significantly different between the mature Rottweiler and Racing Greyhound, although the ratio was greater in the Rottweiler than the Racing Greyhound for both the mature and immature animals.

5.12.6 STATIC HINDLIMB ANGULAR MEASUREMENTS

The mean (SD) standing hindlimb joint angles in the mature and immature Rottweilers and Racing Greyhounds are given in table 5.6.

There were no statistically significant differences between the left and right sides of the mature aniamls in either breed.

MATURE (table 5.6)

The mean combined angle of the pelvis to the horizontal (pelvic angle) in the Rottweiler (22 7° (SEM 1.1°)) statistically significantly less [a] ($p<0.0001$) than the Racing Greyhound (33.6° (SEM 0.9°)). The Rottweiler mean hip angle was statistically significantly more flexed [b] ($p<0.001$) than the equivalent Racing Greyhound angle. The mean Rottweiler hock angle was also statistically significantly more flexed [c] ($p<0.0001$) than the Racing Greyhound hock.

There were no statistically significant differences between the Rottweiler and Racing Greyhound mean joint angle flexions of the stifle joint (149.4 ° (SEM 1.6 °) and 147.2 ° (SEM 1.3°)), metatarsophalangeal joint (140.4 ° (SEM 3.1°) and 137.0 ° (SEM 2.3 °)), and retraction angle (-10.9 ° (SEM 1.2 °) and -10.4 ° (SEM 1.3 °)) respectively (table 5.6).

IMMATURE (table 5.6)

There was a noticable difference in the mean flexion angles of a number of the hind limb joints measured. The mean standing pelvic and hip angles in the Rottweiler were noticeably less than the Racing Greyhound. The mean hock and metatarsophalangeal flexion angles in the Rottweiler were also noticeably less than in the Racing Greyhound. The mean stifle joint and retraction angles were similar in both Rottweilers and Racing Greyhounds.

MATURE VERSUS IMMATURE

There were no noticeable differences between the hindlimb joint angle flexions of the mature and immature animals, except the metatarsophalangeal angles. This appears to be due to a genuine lack of difference between the mature and immature animals of the same breed, rather than the large deviation about the mean values from a small sample size (table 5.6).

5.12.7 DYNAMIC TEMPORAL AND SPATIAL GAIT PARAMETERS

The total number of gait cycles analysed were;

	ROTTWEILER				**RACING GREYHOUND**			
	MATURE		**IMMATURE**		**MATURE**		**IMMATURE**	
	Walk	**Trot**	**Walk**	**Trot**	**Walk**	**Trot**	**Walk**	**Trot**
Left	56	49	11	10	80	79	7	7
Right	46	53	6	8	73	62	7	10
Total	**102**	**102**	**17**	**18**	**153**	**141**	**14**	**17**

The mean (SD) number of consecutive gait cycles analysed for each period of locomotion were;

	ROTTWEILER		RACING GREYHOUND	
	MATURE	**IMMATURE**	**MATURE**	**IMMATURE**
Walk	3.7	3.7	3.7	3.5
SD	(0.6)	(0.6)	(0.5)	(0.7)
SEM	(0.06)	(0.14)	(0.04)	(0.19)
Trot	3.3	3.0	3.5	3.4
SD	(0.5)	(0.8)	(0.6)	(0.5)
SEM	(0.05)	(0.19)	(0.05)	(0.13)

Not all the periods of locomotion in each dog were suitable for gait analysis at both walk and trot, on both the left and right sides. Therefore the number of dogs which had their gaits analysed at walk and trot are given below.

	ROTTWEILER		RACING GREYHOUND	
	Mature	**Immature**	**Mature**	**Immature**
Walk	22	3	23	2
Trot	20	2	21	2

The footfall (gait) patterns of both the Rottweiler and the Racing Greyhound, at walk and trot, were symmetrical gaits, lateral sequence, lateral couplet. LH - LF - RH - RF - LH - LF ...

where a hind footfall is followed by a forefoot on the same side (see 4.6).

5.12.7.1 TEMPORAL PARAMETERS

The mean values, at walk and trot, of the temporal gait parameters of mature and immature Rottweilers and Racing Greyhounds, measured from the recorded high speed cinefilm, are illustrated in table 5.7 to table 5.10. The values of the left, right and both sides combined, for the mean speed, stance, swing and gait cycle duration, duty factor and Froude number are given.

Speed of locomotion (tables 5.7 to 5.10)

There were no statistically significant differences between the mean speeds of walking locomotion when the left and right hindlimb gait parameters were measured for the mature Rottweiler or the mature Racing Greyhound. There were no statistically significant differences between the mean speeds of trotting locomotion when the left and right hindlimb gait parameters where measured for the mature Rottweiler or the mature Racing Greyhound (table 5.8). The mean combined values of the speed of the mature Rottweiler at walk (1.17m/s (SEM 0.03m/s)) was not statistically significantly different from the mean combined value of the mature Racing Greyhound (1.12m/s (SEM 0.03m/s). The mean combined values at trot were also not statistically significantly different (Rottweiler 2.07m/s (SEM 0.05m/s), Racing Greyhound

1.99m/s (SEM 0.04m/s)). The mean combined speed of locomotion of the mature Rottweiler at walk (1.17m/s (SEM 0.03m/s)) was statistically significantly lower (paired t test $p<0.0001$) than that of the Rottweiler at trot (2.07m/s (SEM 0.05m/s)), as were the mature Racing Greyhound speeds at walk and trot (1.12m/s (SEM 0.03m/s) and 1.99m/s (SEM 0.04m/s)) ($p<0.0001$).

As seen with the mature group, the mean speeds of locomotion in the immature group (tables 5.9 and 5.10) were noticeably different between the mean walking and trotting speeds of the Rottweilers and the Racing Greyhound.

MATURE

At walk, in the mature group, table 5.7 shows the mean (SD) temporal gait parameters of mature Rottweilers and Racing Greyhounds. The swing, stance and gait cycle durations, duty factors and Froude numbers are given. There were no statistically significant differences between the mean values of the left and right hind limbs of each breed, nor between the combined left and right means of the Rottweilers and Racing Greyhounds, except the mean Froude number of the Rottweiler (0.26 (SEM 0.01)) was statistically significantly greater ($p<0.01$) than that of the Racing Greyhound (0.22 (SEM 0.01)).

At trot, (table 5.8) there were no statistically significant differences between the mean values of the left and right hindlimbs in either the Rottweiler or Racing Greyhound. However, unlike the mean values measured at walk, the mean values at trot of the stance phase duration of the Rottweiler (0.26s (SEM 0.01s) was statistically significantly longer [a] ($p<0.0001$) than the Racing Greyhound (0.23s (SEM 0.01s). The mean Rottweiler swing phase duration (0.29s (SEM 0.01s) was statistically significantly shorter [b] ($p<0.05$) than that of the Racing Greyhound (0.31s (SEM 0.01s). The mean duty factor was statistically significantly more [c] ($p<0.0001$) for the Rottweiler (46.5% (SEM 0.8%)) than in the Racing Greyhound (42.4% (SEM 0.7%). Because the mean Rottweiler stance phase was statistically significantly longer and the swing phase significantly shorter than the Racing Greyhound, there was no statistically significant difference between the gait cycle durations of the two breeds (Rottweiler 0.55s (SEM 0.01s), Racing Greyhound 0.53s (SEM 0.01s)).

The mean Froude number of the Rottweiler was statistically significantly less [d] ($p<0.001$) than that of the Racing Greyhound.

IMMATURE

At walk, (table 5.9), the values of the temporal gait parameters for the left and right hindlimbs of each breed were similar. The mean combined stance, swing and gait cycle durations were shorter for the Rottweiler than the Racing Greyhound, although there was a noticeable standard deviation about the mean for all these parameters. The mean duty factor of the Rottweiler (61.9%) was similar to that of the Racing Greyhound (60.0%).

The mean Froude number of the Rottweiler was noticeably greater than the Racing Greyhound.

At trot, (table 5.10), the values of the temporal gait parameters for the left and right hindlimbs of each breed were similar, although they showed more variation than at walk. The mean stance phase of the Rottweiler was noticeably greater than the Racing

Greyhound (0.27s) and 0.23s respectively). The mean swing phase duration of the Rottweiler however (0.27s) was less than that of the Racing Greyhound (0.28s). The mean gait cycle duration of the Rottweiler slightly longer than that for the Racing Greyhound. Therefore the mean duty factor for the Rottweiler was noticeably greater (50.2%) than the mean Racing Greyhound value (44.6%).

The mean Froude number of the Rottweiler was greater than that of the Racing Greyhound.

MATURE VERSUS IMMATURE

At walk, (table 5.7 and 5.9), the mean swing phase duration of the mature Rottweiler (0.31s (SEM 0.05s)) was noticeably longer than the immature Rottweiler (0.26s). The mean gait cycle duration was also longer in the mature (0.80s (SEM 0.01s)) compared to the immature Rottweiler (0.69s).

At trot, (table 5.8 and 5.10), the mean swing phase duration of the mature Racing Greyhound (0.31s (SEM 0.05s)) was noticeably less than the immature Racing Greyhound (0.28s). In the Rottweiler, the mean duty factor of the mature group (46.5% (SEM 0.8%)) was noticeably lower than the immature group (50.2%).

5.12.7.2 GAIT FORMULAE (see 4.9)

The mean gait formulae (SD) of the mature Rottweilers and Racing Greyhounds at walk and trot are given in table 5.11 and the individual gait formulae of the Rottweilers and Racing greyhounds at walk and trot are shown in fig 5.15.

At walk, the mean gait formula of the Rottweiler (60 : 19) was statistically significantly different [a] ($p<0.001$) from those of the Racing Greyhound (61 : 26). It was the percentage of the gait cycle that the forelimb foot fall lags behind the hindlimb on the same side (relative phase), that was different, rather than the duty factor.

At trot, the mean gait formulae of the Rottweilers and Racing Greyhounds were still statistically significantly different [b] ($p<0.0001$) (47 : 52 and 42 : 54 respectively) but it was the difference between the duty factors which was significantly different.

5.12.7.2 TRIGONOMETRICALLY DETERMINED STIFLE JOINT ANGLES

The stifle joint angles of the mature Rottweilers ($n = 7$) and Racing Greyhounds ($n = 7$) at walk and trot, calculated trigonometrically from the femur, tibia and greater trochanter to lateral malleolus lengths, are illustrated and compared to the values measured directly from the skin markers in table 5.12.

At walk, there were no statistically significant differences between the mean values of the maximum extension of the stifle joint for either the Rottweilers or the Racing Greyhounds measured directly or calculated trigonometrically.

The value of the mean maximum stifle joint flexion for the Rottweiler was not statistically significantly different when measured directly compared to the calculated value. The range of motion of the joint was, however, statistically significantly greater [a] (paired t test $p<0.01$) when calculated trigonometrically (50.7 ° (SEM 1.4 °))

compared to being measured directly (44.1 ° (SEM 2.4 °)). For the Racing Greyhound, the mean maximum joint flexion measured directly was not statistically significantly different from that calculated trigonometrically. The range of motion was significantly greater [b] ($p<0.01$) when calculated (37.4 ° (SEM 1.7 °)) compared to direct measurement (32.3 ° (SEM 1.9 °)).

At trot, the maximum stifle joint flexion in the Rottweiler was statistically significantly greater [c] ($p<0.0001$) when calculated (88.2 ° (SEM 2.9 °)) rather than measured directly (105.8 ° (SEM 2.3 °)). The same was true for the Racing Greyhound [d] (calculated 96.8 ° (SEM 1.3 °), measured 105.1 ° (SEM 2.5 °)). The mean maximum joint extension in the Rottweiler was statistically significantly greater [e] ($p<0.05$) when measured directly (163.0 ° (SEM 2.2 °)) compared to the calculated values (159.9 ° (SEM 1.7 °)). In contrast, the mean maximum joint extension in the Racing Greyhound measured directly was not significantly different from that when calculated. The range of motion of the joint was also statistically significantly greater [f,g] ($p<0.001$) when calculated (Rottweiler 71.7 ° (SEM 2.7 °), Racing Greyhound 58.3 ° (SEM 2.2 °) compared to being measured directly (Rottweiler 57.2 ° (SEM 1.5 °), Racing Greyhound 48.2 ° (SEM 1.4 °)).

There were statistically significant differences between the two methods, especially at trot and when measuring the maximum joint flexion angles, but there were no statistically significant differences in the maximum extension angles between the two methods at walk in either breed, and the differences between the values determined by the two methods at walk were small. However, because of the movement of the skin over the stifle area reported in other studies (Wentink 1976, Goslow et al 1981, van Weeren and Barneveld 1986, Pratt and Loeb 1991) and the statistically significant differences found between the measured and calculated joint angles, the stifle joint angle data presented in this chapter, refers to those values calculated trigonometrically from the femur, tibia and greater trochanter to lateral malleolus lengths.

5.12.7.3. SPATIAL PARAMETERS

The mean combined right and left values at walk and trot of the spatial gait parameters of mature Rottweilers and Racing Greyhounds measured from the recorded high speed cinefilm are illustrated in tables 5.13 and 5.14. The mean values for the maximum flexion, maximum extension and range of motion of hind limb joint movement are given.

There were no statistically significant differences between the left and right hindlimb spatial parameters of the Rottweilers and Racing Greyhounds at walk or trot (not illustrated here).

MATURE

At both walk and trot in the mature groups, most of the mean, combined left and right hindlimb joint angle values for the Rottweiler were statistically significantly different from those of the Racing Greyhound.

At walk, (table 5.13), the range of pelvic angle movement during the gait cycle was statistically significantly greater [c] ($p<0.0001$) in the Rottweiler compared to the Racing Greyhound.

There was a greater maximum flexion of the hip in the Rottweiler compared to the Racing Greyhound [d].

There was a statistically significantly greater [e,f] ($p<0.0001$) maximum extension and range of motion of the Rottweiler stifle joint (163.4 $^{\circ}$ (SEM 1.2 $^{\circ}$) and 50.7 $^{\circ}$ (SEM 0.8 $^{\circ}$)) compared to the Racing Greyhound (153.1 $^{\circ}$ (SEM 0.7 $^{\circ}$) and 37.1 $^{\circ}$ (SEM 0.9 $^{\circ}$)). There was no statistically significant difference between the mean maximum flexion of the Rottweiler stifle joint (112.6 $^{\circ}$ (SEM 1.4 $^{\circ}$)) compared to the Racing Greyhound (116.1 $^{\circ}$ (SEM 0.7 $^{\circ}$)) ($p = 0.06$).

At the hock joint, although the mean maximum extension values were not statistically significantly different between the Rottweiler and the Racing Greyhound, the mean maximum flexion and range of motion of the Rottweiler were statistically significantly greater [g,h] ($p<0.0001$) than those of the Racing Greyhound.

The mean angles of protraction, retraction and pace angle in the Rottweiler (-30.6 $^{\circ}$ (SEM 0.6 $^{\circ}$), 26.7 $^{\circ}$ (SEM 0.6 $^{\circ}$) and 57.3 $^{\circ}$ (SEM 0.8 $^{\circ}$) respectively) were statistically significantly greater [k, l, m] ($p<0.0001$) than those of the Racing Greyhound (-25 .7 $^{\circ}$ (SEM 0.5 $^{\circ}$), 21.7 $^{\circ}$ (SEM 0.4 $^{\circ}$) and 47.5 $^{\circ}$ (SEM 0.7 $^{\circ}$) respectively).

At trot, (table 5.14), the trends in the differences between the two breeds were similar to those seen at the walk, but the absolute values of the mean maximum flexion, extension and range of motion changed.

The range of motion of the pelvic angle during the gait cycle was still statistically significantly greater [c] ($p<0.0001$) in the Rottweiler compared to the Racing Greyhound but both values were lower than those seen at walk (table 5.13).

The mean maximum flexion and extension of the Rottweiler hip joint were statistically significantly different [d, e] ($p< 0.01$ and $p< 0.0001$) from those of the Racing Greyhound but the mean range of motion between the two breeds were not significantly different.

The mean maximum flexion of the stifle joint was statistically significantly greater [f] ($p<0.001$) in the Rottweiler (88.2 ° (SEM 1.7 °)) compared to the Racing Greyhound (97.0 ° (SEM 0.8 °)), however, the difference in the maximum extension between the two breeds was not statistically significantly different (Rottweiler 159.9 ° (SEM 1.0 °), Racing Greyhound 154.4 ° (SEM 0.8 °)). The mean range of stifle joint motion was statistically significantly greater [g] ($p<0.001$) in the Rottweiler (71.7 ° (SEM 1.6 °)) compared to the Racing Greyhound (57.4 ° (SEM 1.2 °)). The mean range of motion was also statistically significantly greater ($p<0.0001$) at the trot compared to the walk in both the Rottweiler (trot 71.7 ° (SEM 1.6 °), walk 50.7 ° (SEM 0.8 °)) and Racing Greyhound (trot 57.4 ° (SEM 1.2 °), walk 37.1 ° (SEM 0.9 °)). The mean maximum extension of the stifle joint at trot in both the Rottweiler (159.9 ° (SEM 1.0 °)) and the Racing Greyhound (154.4 ° (SEM 0.8 °)) were not statistically significantly different from the values of these breeds at walk (Rottweiler 163.4 ° (SEM 1.2 °), Racing Greyhound 153.1 ° (SEM 0.7 °)), however, the mean maximum flexion in the Rottweiler at trot (88.2 ° (SEM 1.7 °)) was statistically significantly greater

($p<0.0001$) than those measured at the walk (112.6 ° (SEM 1.4 °)). The same was true for the Racing Greyhound.

The hock joint exhibited the same pattern as the stifle joint, with an increased range of motion at the trot compared to the walk. Again, there was no statistically significant increase in the maximum extension of the hock at the trot compared to the walk in either breed, but there was a statistically significant increase ($p<0.0001$) in the maximum flexion of the hock at the trot compared to the walk in the Rottweiler and in the Racing Greyhound.

The pace angle was statistically significantly greater [n] ($p<0.001$) in the Rottweiler (53.6 ° (SEM 0.9 °)) compared to the Racing Greyhound (45.3 ° (SEM 0.8 °)). The pace angles at the trot, in both the Rottweiler and Racing Greyhound (53.6 ° (SEM 0.9 °) and 45.3 ° (SEM 0.8 °) respectively) were statistically significantly less ($p<0.01$) than the equivalent values for the breeds at walk (57.3 ° (SEM 0.8 °) and 47.5 ° (SEM 0.7 °) respectively).

The mean ranges of motion of all the hind limb joint angles measured at walk were statistically significanlty different from those measured at trot, with the exception of the Rottweiler metatarsophalangeal joint.

Figures 5.16 - 5.19 show the mean stifle and hock joint angle changes of the Rottweiler and Racing Greyhound, at walk and trot, plotted against time.

The pattern of movement of the stifle and hock joints in both breeds are similar, but the magnitude of the movement during the gait cycles are greater in the Rottweiler compared to the Racing Greyhound. This is illustrated by the values recorded in tables 5.13 and 5.14 as well as in fig 5.16 to 5.19.

At walk (fig 5.16 and 5.17), during the stance phase, the stifle joint angle changes very little and exhibits only slight joint flexion throughout the majority of the stance phase. This joint flexion is seen more in the Rottweiler than the Racing Greyhound. Immediately prior to the end of the stance phase, the stifle joint flexes noticeably. The hock joint flexes initially and then extends prior to the start of the swing phase, reaching its maximum extension at the transition from the stance to swing phase. During the swing phase, the stifle joint continues to flex and then extends rapidly to prepare for foot placement. The hock joint also follows this pattern, but lags behind the movement changes of the stifle joint, that is, the hock joint maximally flexes and commences extension after the stifle joint.

At trot (fig 5.18 and 5.19), the same patterns of stifle and hock joint movement are seen, but the magnitude of the angle changes are greater compared to the walk in both breeds.

5.13 DISCUSSION

Although the walking and trotting gaits of 28 Rottweilers and 28 Racing Greyhounds were analysed, only 3 dogs of each breed were immature (6-8 months old). This was due to a lack of available subjects. Most of the Racing Greyhounds were bred in Ireland and only came to Great Britain to start training at 10-12 months of age. The access to Rottweiler puppies was also limited. Although the data collected from the immature dogs are presented here and in the following chapter, the small sample size should be borne in mind when considering the mean values of the immature dogs both between breeds and during comparison with the mature dogs.

As expected, the mean body weights of the immature dogs were noticeably less than those of their adult equivalents and also the Rottweilers were heavier than the Racing Greyhounds. The mean percentage body weight supported by the front and hindlimbs does not appear to change between the immature and mature dogs and there was no breed variation in the percentage body weight carried.

The mean framing rate of the cinecamera was not 64 frames per second (fps) as expected from the camera setting, but the mean value of 50.1 fps varied very little with a standard deviation of only 1.2fps (see pages 113 and 120). Therefore a time interval of 0.02s (1/50th second) between each frame was used throughout the study.

The optical distortion of the cinefilm image resulting from recording the subject using the panning method, was readily demonstrated by the variation in the measured distance between the equidistant ground tapes, the measured poles and the apparent changes in the angle of the ground tapes to the vertical (fig 5.4). No marked variations were observed following the trolley recording method. There were no significant differences between the stifle joint angle measurements recorded by the two methods. However, from fig 5.11, and the standard deviations from the means given in table 5.2, there was more variation in the mean maximum values of the stifle joint angles when recorded by panning rather than by the trolley method.

The stifle joint angle changes of the same gait cycles, measured manually and by the Videoplan image analyser and illustrated in figs 5.13 to 5.15, show that both methods appear similar in accuracy and repeatability. Although the frame by frame measurements of the kinematic gait parameters from the cinefilm using the Videoplan is still time-consuming, it is quicker than the manual method and just as accurate.

As there were no statistically significant differences between the measured values of the static morphometric measurements of the left and right hind limbs in either breed, mature or immature, the animals hindlimbs were, as expected, symmetrical.
In the mature Rottweilers, the mean lengths of the functional tibia and metatarsus were shorter than those of the Racing Greyhound, but there was no significant difference between the mean lengths of the femur and paw of the Rottweiler and Racing Greyhound. Therefore, the sum total length of the hindlimb bones was greater in the Racing Greyhound than the Rottweiler. The greater the proportion of the total

limb length which comprises the distal limb segments (tibia and metatarsus), the greater the adaption to cursorial locomotion.

The mean hip height and limb length of the Rottweiler were less than those of the Racing Greyhound, which implies that either the sum total length of the hindlimb bones was greater in the Racing Greyhound, and/or, the hindlimb is straighter in the standing Racing Greyhound than the Rottweiler, so that the functional length is longer. The former statement is correct when the mean hindlimb bone lengths are totalled. The latter statement is also true. The mean values of the standing hindlimb joint angles (table 5.6) show that there was no significant difference between the stifle angles in the two breeds, but the hock joint was more extended in the Racing Greyhound.

The body length of the Rottweiler was shorter than the Racing Greyhound, but the ratios of body length/limb length were similar in each breed because the dogs with the shorter body length also had the shorter limb length. In the immature dogs, as in the mature group, the tibia was longer, the hip height and body length greater in the Racing Greyhound. Therefore as the dogs matured between 6 months and 1 year, the ratio of the tibia to femoral length remains approximately the same in each breed, as does the body length/limb length ratio. Comparing the immature and mature Rottweilers, the tibia is the only measured bone length which significantly increases with maturity. In the Racing Greyhound, the metatarsi are the only measured hindlimb bone which significantly increase in length between 6-8 months and 1-3 years.

Despite the fact that the dogs were moved around between taking the still photographs of one side and then the other, there were no statistically significant differences between the mean angular values of the left and right hindlimbs in either breed. The slope of the pelvis was less in the Rottweiler than the Racing Greyhound, which contributed to the greater degree of hip joint flexion, the angle between the slope of the pelvis and the long axis of the femur, in the standing Rottweiler compared to the Racing Greyhound. The standing stifle joint angles were not significantly different between the breeds, but the hock joint was more flexed in the Rottweiler than the Racing Greyhound.

There were no noticeable differences between the standing angle values of the immature dogs, and the differences in the standing angles of the two breeds were the same as for the mature dogs.

The walking and trotting speeds of the mature and immature, Rottweilers and Racing Greyhounds were not significantly different, which is important when looking at the other measured temporal gait parameters, as these are dependent on the speed of locomotion.

The differences in the temporal parameters between the two breeds were insignificant at walk, each breed having a duty factor of approximately 60%.

During trotting, however, although the mean gait cycle durations of each breed were similar, the duty factor of the Rottweiler was greater than that of the Racing Greyhound. The hindlimbs of the Rottweiler remained in contact with the ground for a longer time, relative to the total gait cycle duration, than the Racing Greyhound. This is illustrated by the mean gait formulae of the walking and trotting Rottweiler compared to the Racing Greyhound, where the percentage of the gait cycle the forelimb footfall lags behind the hindlimb and the duty factors reflect the different temporal patterns of the footfalls of the two breeds.

At walk and trot in both breeds, the mean ranges of stifle joint movement were significantly greater when the angles were calculated trigonometrically rather than directly measured. There were no significant differences in the mean maximum extension of the stifle joint determined by the two methods. Direct measurement of the stifle joint angles significantly underestimated the degrees of maximum joint flexion. This implies that the greatest amount of skin movement over the stifle joint during the gait cycle occurs at joint flexion rather than joint extension.

In a mature, walking dog, the range of movement of the pelvic axis relative to the horizontal, was greater in the Rottweiler. The pace angle was significantly greater in the Rottweiler compared to the Racing Greyhound, This is reflected in the greater maximum hip joint flexion and maximum stifle joint extension in the Rottweiler at foot placement. The ranges of motion of the stifle and hock joints of the Rottweiler during the gait cycle were greater than those of the Racing Greyhound. This was due to a greater maximum extension of the stifle joint and a greater maximum flexion of the hock joint compared to the Racing Greyhound.
During trotting, the pace angle was still greater in the Rottweiler, but both the Rottweiler and the Racing Greyhound pace angles were less at trot than at walk. This implies that the dogs of both breeds 'stride out' more at walk than at trot, and the Rottweilers 'stride out' more than the Racing Greyhounds.

At trot, the maximum stifle joint extension is still greater in the Rottweiler although there is little difference between the values at walk and trot in the same breed. The stifle joint flexes more at trot than walk in both breeds, as does the hock joint.

The standing joint angles, maximum flexions, maximum extensions and ranges of motion of the hindlimb joints of both breeds during locomotion, determined in this section of the study, are in broad agreement with those of other studies (table 5.15 and 5.16).

5.14 CONCLUSIONS

1. The mean percentage of the total body mass supported by the forelimbs was 60% in both the mature and immature dogs, in both Rottweilers and Racing Greyhounds.

2. The morphometric dimensions and the standing joint angles of the left and right hindlimbs of individual dogs were symmetrical.

3. The distal segments of the Racing Greyhound hindlimbs (tibia and metatarsus) were longer, relative to the total limb length, than the Rottweiler, which indicates a greater adaption to efficient cursorial locomotion in the Racing Greyhound.

4. There were no statistically significant differences between the stifle joint angles of the standing Rottweilers and Racing Greyhounds.

5. At walk, the hind feet of both mature and immature, Rottweilers and Racing Greyhounds stayed in contact with the ground for the same percentage of the total gait cycle duration. At trot, the Rottweiler hind feet remained in ground contact for a greater percentage of the gait cycle duration than the Racing Greyhound at the same speed of locomotion.

6. Direct measurement of the stifle joint angles using the skin marker over the lateral femoral epicondyle as a landmark, resulted in an underestimation of the maximum stifle joint flexion in both breeds, but there was no effect on the determination of the maximum joint extension.

7. The Rottweiler extends the stifle joint and flexes the hip joint to a greater degree than the Racing Greyhound, resulting in a greater pace angle. The pace angle is less at trot than at walk in both breeds.

8. The range of joint movement during the gait cycle increases with the speed of locomotion.

9. The increased range of stifle joint movement at trot compared to walk, is due to an increase in the maximum flexion angle in both breeds rather than an increase in the maximum extension.

CHAPTER SIX

CANINE KINEMATIC GAIT ANALYSIS USING A MICROCOMPUTER

6.1 INTRODUCTION

An ideal gait analysis system was proposed by Leach (1987a), the criteria for which have been summarised in chapter 4. There is, to date, no gait analysis system which meets all these ideals, although numerous methods of animal locomotion gait analysis, both kinetic and kinematic, have been described (chapter 4).

This chapter describes the basic function, modification and validation of a kinematic gait analysis system ("Gaitway"), using a microcomputer, which was originally developed for use in humans (Law 1987).

The chapter goes on to describe the use of this system for the analysis of the walking and trotting gaits of normal Rottweilers and Racing Greyhounds, complementing the high speed cinematographic method detailed in chapter 5.

The Gaitway system provides accurate, rapidly available kinematic data in a simple manner and it overcomes some of the disadvantages of other systems which include delays in analysing the recorded data, operating costs and the need for technical operating staff (Law 1987, Wingfield et al 1993).

6.2 MATERIALS

The dogs used in this series of gait recordings were the same as those used for the high speed cinematography. The number of dogs, Rottweiler or Racing Greyhound, mature or immature, recorded using the original or modified Gaitway system are given below.

	ROTTWEILER		RACING GREYHOUND		TOTAL
	mature	**immature**	**mature**	**immature**	
Original Gaitway	7	2	9	2	**20**
Modified Gaitway	18	1	16	1	**36**
Total	**25**	**3**	**25**	**3**	**56**

6.3 THE ORIGINAL GAITWAY SYSTEM

Details of the original Gaitway system have been reported previously (Law 1987) and only a brief description is given here to assist in the understanding of the modifications made to the system to allow the recording and analysis of canine gaits in this study. The Gaitway system measures certain spatial and temporal parameters of gait which will be detailed below.

The system makes use of two hole-punched computer tapes, one is attached to each foot of the subject by adhesive tape. The hole-punched tapes are made of paper-coated plastic and they are strong, do not stretch under tension and do not tear easily. The holes are accurately spaced at intervals of 1/10th inch along one side, lateral to the midline. These tapes run through a floor-mounted reading head assembly which

contains two optical readers, an electronic counter and other electronic processing components, linked to a microcomputer[a] via an 8-bit parallel cable. The optical readers detect the holes in the tapes moving through as the subject walks and the number of holes is counted and stored by the local counter. At a rate of 256 times per second the microcomputer records the local counter reading, i.e. the number of holes which have passed through the optical readers, or the total tape movement up to this time.
Because the inter-hole spacing and the sampling rate are known, the microcomputer accurately calculates the required temporal and spatial kinematic data. It displays these in tabular form on a VDU or in hard copy, for all the gait cycles recorded, the stride lengths, swing phase durations and double support times (see below), the average walking speed (metres per second,m/s) and the cadence (steps/min). Finally it plots the foot velocity during the swing phase versus time for each foot and each gait cycle (points are plotted every 1/24s) (fig 6.1).
Double support time is the time during the gait cycle when both hind feet are stationary on the ground simultaneously.

The microcomputer has only one parallel input/output port, therefore the counts arising from the movements of the left and right tapes are combined in the local counter and it is the sum of the two movements which is stored in the microcomputer memory rather than the data from the individual tapes. This is acceptable in the measurement of human walking since there are always two periods in each gait cycle when the two feet are simultaneously stationary in contact with the floor, and by

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[a] Einstein, Tatung

detecting these "double support" periods, appropriate algorithms in the computer program can be used to note the transfer of movement from one limb to the other. If the subject is instructed to "start with the right foot" the data can be correctly assigned to the left and right limbs.

6.4 THE MODIFIED GAITWAY SYSTEM (fig 6.2)

While trying to use the original Gaitway system to record the canine walking gait, a number of difficulties were encountered;

1. The dogs would not tolerate adhesive tape attached directly onto the digits or pads, nor would they tolerate any type of shoe to which the hole-punched tapes could be attached.

2. No reliable method was available to ensure that the dogs started to walk with a particular hindfoot, therefore the data recorded could not always be correctly assigned to the left and right hind feet by the microcomputer. An independent, unambiguous method of assigning the tape movements was needed.

3. During quadrupedal locomotion, especially with the tape attachment used and at greater speeds, the double support period of the hindlimbs was short or non-existent and was not consistently recognised by the microcomputer. In this event, the change in movement from one hindfoot to another was not registered by the microcomputer and the temporal and spatial parameters were incorrectly calculated.

The problem of attaching the hole-punched tapes to the hindlimbs was solved by using a length of monofilament nylon line tied around the hindlimbs, just proximal to the metatarsophalangeal joint to which the computer tapes were attached. It was well tolerated by the dogs and resulted in firm fixation of the tapes. Dogs required a period of familiarisation to the tape attachments, reading head drag and minor noise of the Gaitway system, by having some practice walks with the tapes attached. The majority of the dogs required only 4-6 walks to become accustomed to the system. Of 96 dogs, of various breeds, which have been walked attached to the system, only 8 (8.3%) failed to tolerate the tapes.

To overcome the problems of distinguishing the left and right hindfeet movements, the original Gaitway system was modified to consist of two electronically independent systems, one for each hind foot. The hole-punched tapes from each hind foot pass through a reading head assembly containing two independent optical readers and two independent local counters. The left side tape, optical reader and local counter are coupled to one microcomputer, the right side to a separate, but identical microcomputer, each with a VDU (fig 6.2). Care must be taken during the set-up of the equipment to ensure that the output of a particular optical reader is correctly coupled to a particular microcomputer. The original software program is used in each computer during data collection. Although both hind feet are recorded during the same walk, to allow comparison between left and right hind feet movements and the interlacing of the foot velocity versus time plots, both sides must start recording data simultaneously whichever foot moves first. The electronic circuits were therefore modified to include two bistables (flip-flops) and cross-coupling circuitry which delivers a single pulse to the contralateral counter when either of the two readers detects the first tape movement. These are 'set' by means of two push buttons immediately before the test walk is to begin. Non-flashing, amber lights on the reading head assembly indicate when the bistables are 'set'. Both bistables are 'reset' by the first detected movement of **either** tape, which instructs both microcomputers to begin data collection. On detection of the first tape movement, alternately lit red and green lights and the appearance of asterisks on both VDUs, indicate that data collection is in progress. The time bases of the two records are thus accurately synchronised and they may be combined later into a single display along a common axis (fig 6.3). Twenty five (25) seconds are allocated for data collection which is sufficient to record approximately thirty (30) walking gait cycles of an average Rottweiler or Racing Greyhound. The subject should remain stationary after the bistables are 'set' until the microcomputers have been primed to record the data collected by the optical readers, at which time, the dog should be encouraged to reach and maintain a normal, regular gait pattern as soon as possible. The recorded data is presented in the same format on a VDU as the original Gaitway system but all the data shown on one VDU will have come entirely from the left or right foot. Extra program has been written and is used following data collection to print or display the interlaced foot velocity versus time plots for alternate left and right swing phases for the entire walk. Therefore the left and right foot parameters are seen sequentially and in correct temporal relationship (fig 6.3). The adapted Gaitway system does not rely on detection of a double support time of the hind feet to function, so it can also analyse the trotting gait where there is no period in the gait cycle when both hind feet are simultaneously stationary on the ground.

As with the high speed cinematography, between 3 and 5 consecutive gait cycles are analysed to obtain a meaningful analysis of the gait (Hildebrand 1965, Fredricson 1972, Drevemo et al 1980a). The analysed gait cycles were from mid-walk when the subject had settled into its usual, even gait pattern.

Before the Gaitway system was modified, the original system was used to record the gaits of 10 Rottweilers and 10 Racing Greyhounds. Because of the inability of the microcomputer to consistently recognise the canine hind limb double support period, it was not possible to record both hind limbs during the same period of locomotion. Therefore only one tape was used to record the kinematic events of one hind limb at a time. This method of recording was the basis of the modification of the system to record both hindlimbs independently but synchronously. As determined in chapter 5, there were no statistically significant differences between the left and right hind limb gait parameters of individuals recorded during different periods of locomotion. Therefore, it is valid to combine the values of the left and right hind limbs, recorded with the original Gaitway system, and group them with those recorded with the modified system. Attaching only one tape to one hindlimb and leaving the contralateral limb 'free', may affect the symmetry of movement of the hind limbs. Therefore the other tape, which was not required to record data, was still attached to the appropriate hind limb but was positioned in the reading head assembly so that no data was collected.

6.5 ACCURACY OF THE GAITWAY RECORDING SYSTEM

To verify the accuracy of the graphic and tabular data from the Gaitway system during locomotion, two questions must be addressed;

a, Does the machine measure times and distances accurately?

b, Does the walk, measured with the machine attached to the animal, accurately depict the spontaneous walk?

The first question was examined during the development of original Gaitway system in 1984 (Law 1994) using a special, pre-punched tape. This tape consisted of a series of holes, 1/10th inch apart, punched in a pre-designated pattern to simulate regular gait cycles including double support periods. That is, 128 holes (first step) followed by 64 'blanks' (double support period), then 256 holes (swing phase) followed by 64 'blanks' then 256 holes, 64 'blanks' etc. to represent a total of 5 gait cycles. The tape was passed through the optical reader at a steady velocity of 1.93m/s and the times and distances were displayed by the Gaitway system (Fig. 6.4).
Because the velocity of the tape and the spacing of the holes and blanks (swing and double support phases) were known, the data calculated by the system can be compared with the known parameters of the simulated gait cycles.

Verification of the swing phase duration;

Tape velocity	=	1.93 m/s		
Swing phase	=	256 holes		
	=	25.6 inches		
	=	0.650 metres		
Swing phase duration	=	0.650/1.93	=	0.337 s

This compares favourably with that seen in Fig. 6.4

Verification of gait cycle duration (swing phase + double support phase);

	=	256 holes + 64 blanks		
	=	320 'holes'		
	=	32.0 inches	=	0.8128 metres
Gait cycle duration	=	0.8128/1.93	=	0.421 s

This compares favourably with that seen in Fig. 6.4 (0.338s + 0.082s = 0.420s).

Verification of stride length, thc distance the tape moves during the swing phase;

256 holes spaced 1/10th inch apart = 25.6 inches = 0.650m

which compares favourably with that seen in Fig. 6.4.

Therefore it was shown by Law (1994) that the machine does measure time and distances accurately.

The accuracy of the presented data with a animal attached to the machine (question b) was addressed in this study.

Dogs (n = 7 Rottweilers and 7 Racing Greyhounds) walking or trotting with the Gaitway system attached were simultaneously recorded with the high speed cinefilm. The temporal and spatial gait parameters of the same gait cycles recorded by the Gaitway system were compared with those measured directly from the cinefilm. The gait parameters measured were; stride length, walking speed, gait cycle, stance phase and swing phase durations and the duty factors. The foot velocity during the swing phase was calculated from the hind limb joint angle changes during the gait cycle, measured by the Videoplan image analyser.

To calculate the foot velocity from the cinefilm, see fig 6.5a and b; where the following geometric parameters were measured,

r_1 = hip angle minus pelvic angle (radians)

r_2 = stifle angle minus r_1 (radians)

r_3 = hock angle minus r_2 (radians)

F = femoral length

T = tibial length

M = metatarsal length

During gait, r_1, r_2 and r_3 are functions of time. Therefore the angles at time t are denoted by $r_1(t)$, $r_2(t)$ and $r_3(t)$. Therefore the time derivative of the angles at time t (the rate of change of r_1 etc. at a specified time) are $r_1(t)$, $r_2(t)$, and $r_3(t)$.

0.02s is the time interval between successive frames (frame interval).

The best approximation to the time derivative is obtained by averaging the change in angle between successive frame by frame intervals.

$$\text{ie.} \qquad \dot{r}_1\,(t + 0.01) \approx \frac{r_1\,(t + 0.02) - r_1\,(t)}{0.02}$$

For simplicity with adequate accuracy;

$$\dot{r}_1(t) \approx \frac{r_1(t + 0.02) - r_1(t)}{0.02}$$

With the angles measured as indicated in Fig. 6.5a and b the foot velocity is

$$\begin{aligned} v_f &= u + F\frac{d}{d_t}(\cos r_1(t)) - T\,\frac{d}{d_t}(\cos r_2(t)) + M\,\frac{d}{d_t}(\cos r_3(t)) \\ &= u - F\sin r_1(t)\cdot \dot{r}_1(t) + T\sin r_2(t)\cdot \dot{r}_2(t) - M\sin r_3(t)\cdot \dot{r}_3(t) \end{aligned}$$

Where u = speed of locomotion (= velocity of the pelvis).

To change the angles from degrees to radians;

$$r = \frac{r_{deg} \times \pi}{180} \text{ radians}$$

From these equations, the foot velocity during the gait cycle has been calculated from the cinefilm and compared with the foot velocity versus time plot presented by the Gaitway system for exactly the same gait cycle.

6.6 THE INFLUENCE OF THE GAITWAY SYSTEM ON NORMAL LOCOMOTION

Incorporated into the tape-movement reading head assembly are adjustable dampers which prevent the overshoot of the tapes through the reading head assembly at foot placement. The drag of the tapes through the reading head assembly is minimal, with an approximate force of only 0.25 newtons being required to move the tapes. Although the drag was minimal, the effect of this and the physical attachment of the tapes to the hindlimbs was evaluated.

The repeatability of gait cycles of an individual subject during different periods of locomotion at the same speed have been discussed (see chapter 4 and 5 and 6.4).

To determine the influence of the Gaitway system on the locomotion of untrained dogs, 6 Rottweilers and 6 Racing Greyhounds were walked or trotted twice at similar speeds, over the same walkway, by the same handler. The dogs were recorded with the high speed cinecamera during locomotion, once with the Gaitway system attached and once without. The temporal and spatial parameters of the two periods of locomotion were measured from the cinefilm and compared. The parameters measured were; stride length, walking speed, stance, swing and gait cycle durations, foot velocity and the hind limb joint angle changes throughout the gait cycle.

Having examined the accuracy and the influence of the Gaitway system, the walking speed, stride frequency, stance, swing, gait cycle durations, stride length, duty factors and maximum foot velocities were recorded in a total of 28 Rottweilers and 28 Racing Greyhounds at walk and trot.

6.7 RESULTS

The tables in this section illustrate the mean values of the various parameters measured, but the statistical analyses (t test) were carried out on the values for each individual recorded.

6.7.1 ACCURACY OF THE GAITWAY RECORDING SYSTEM (see 6.5)

The mean kinematic gait values measured from the cinefilm are compared, in tables 6.1 and 6.2, with the values calculated by the Gaitway system for the same gait cycles. Although 7 Rottweilers and 7 Racing Greyhounds were recorded (section 6.5), not all the recordings were suitable for analysis in all the dogs (5 Rottweilers and 6 Racing Greyhounds suitable). The gait parameters measured were; walking/trotting speeds, stride length, stance, swing and gait cycle durations, duty factor and maximum foot velocity.

There were no statistically significant differences between the mean speeds of locomotion calculated from the cinefilm and the values recorded by the Gaitway system in either breed at walk and trot.

At walk, table 6.1, in the Rottweiler, the mean stance and swing phase durations measured from the cinefilm were statistically significantly different [a, b] (paired t test $p<0.0001$) from the mean gait values of the same gait cycles calculated by the Gaitway system.

The mean gait cycle duration measured from the cinefilm was, however, not statistically significantly different from that measured by the Gaitway system.

Because the mean stance phase durations were statistically significantly longer and the swing phase durations significantly shorter in those measures from the cinefilm, the mean duty factor of the dogs measured from the cinefilm was statistically significantly greater [c] ($p<0.001$) than that calculated by the Gaitway system.

The mean stride lengths were not statistically significantly different when measured from the cinefilm and calculated by the Gaitway system.

There was no statistically significant difference between the mean maximum foot velocity of the Rottweiler measured from the cinefilm and that calculated by the Gaitway system.

In the Racing Greyhound (table 6.1), as in the Rottweiler, the mean stance and swing phase durations measured from the cinefilm were statistically significantly different [d, e] ($p<0.0001$) from the mean values calculated by the Gaitway system.

The mean gait cycle durations measured from the cinefilm and by the Gaitway system were not statistically significantly different.

The mean duty factor measured from the cinefilm was, as for the Rottweiler, statistically significantly greater [f] ($p<0.0001$) than that calculated by the Gaitway system.

The mean stride lengths measured from the cinefim were not statistically significantly different from those calculated by the Gaitway system.

There was no statistically significant difference between the mean maximum foot velocity of the Racing Greyhound measured from the cinefilm and that calculated by the Gaitway system.

At trot, in the Rottweiler (table 6.2) the mean stance and swing phase duration measured from the cinefilm were statistically significantly different [a, b] ($p<0.0001$) from those calculated by the Gaitway system.

The mean gait cycle duration determined by the two methods were not statistically significantly different.

The mean duty factor measured from the cinefilm was significantly greater [c] ($p<0.0001$) than that calculated by the Gaitway system.

The mean stride length of the Rottweiler, measured from the cinefilm was not statistically significantly different from the mean value calculated by the Gaitway system.

There was no statistically significant difference between the mean maximum foot velocity of the Rottweiler measured from the cinefilm and that calculated by the Gaitway system.

In the Racing Greyhound (table 6.2), the mean stance and swing phase durations measured from the cinefilm were statistically significantly different [d, e] ($p<0.001$ and $p<0.0001$ respectively) compared to the mean values calculated by the Gaitway system.

There was no statistically significant difference between the mean gait cycle duration measured from the cinefilm compared to that calculated by the Gaitway system.
The mean duty factors determined by the cinefilm and Gaitway measurement methods were statistically significantly different [f] ($p<0.0001$).
The mean stride length measured from the cinefilm and that calculated by the Gaitway system were not statistically significantly different.
There was no statistically significant difference between the mean maximum foot velocity of the Racing Greyhound measured from the cinefilm and that calculated by the Gaitway system.

The discrepancy between the swing and stance phase durations of the same gait cycles as measured by the cinefilm and the Gaitway system (table 6.1 and 6.2) is probably due to the method of attachment of the hole-punched tapes to the hindlimbs.
The lengthened swing phase recorded by the Gaitway can be caused by tape movement before toe lift-off when the metatarsophalangeal joint, and therefore the attached tape at that point, moves cranially immediately prior to the end of the stance phase. This minor movement will be registered by the Gaitway as the commencement of the swing phase. Although the effect on the recorded stride length will be minimal, the swing phase duration will be extended (Fig. 6.6).
Evidence for this proposal can be obtained by using the time versus distance plots for each walk or trot with a large scale time axis (Fig. 6.7).
Using the walking time versus distance plots recorded from 5 Rottweilers and 6 Racing Greyhounds (section 6.5), the transition points between swing and stance

phases of each gait cycle were inserted. The stance and swing phase durations were measured manually and again compared with the values obtained by simultaneous cinefilm recording, table 6.3.

There were no statistically significant differences between the values determined from the cinefilm and those measured from the time versus distance plots.

This shows that the slight movement of the Gaitway tapes near the end of the stance phase, due to the position of the tape attachment at the metatarsophalangeal joint, accounts for the discrepancy between the stance and swing phase durations recorded by the cinefilm and those calculated automatically by the Gaitway system (table 6.1 and 6.2).

6.7.2 INFLUENCE OF THE GAITWAY SYSTEM ON NORMAL LOCOMOTION (see section 6.6)

The mean (SD and SEM) values of the temporal and spatial kinematic gait parameters of the 6 mature Rottweilers and 6 mature Racing Greyhounds, measured from the cinefilm, with and without the Gaitway system attached are given in tables 6.4 to 6.7. The results were statistically analysed using a paired t test.

Temporal gait parameters

At walk, (table 6.4), there were no statistically significant differences between the mean temporal kinematic gait parameters measured with and without the Gaitway attached in the Rottweiler and Racing Greyhound.

At trot, (table 6.5), there were no statistically significant differences between the mean gait values with and without the Gaitway attached for the Rottweiler. For the Racing Greyhound (N = 3), the mean speed of locomotion was noticeably greater in those trotting periods when the Gaitway was attached (2.14m/s) compared to when it was not (1.93m/s). The mean gait cycle duration of the Racing Greyhound with the Gaitway attached was shorter than when the Gaitway was not attached. The gait cycle frequency was also noticeably greater when the Gaitway was attached compared to when it was not attached.

Spatial gait parameters

At walk, (table 6.6a and b), the only statistically significant differences between the maximum flexion, extension and range of motion of the hindlimb joint angles, with and without the Gaitway attached, were found in the mean range of stifle joint motion in both the Rottweiler and Racing Greyhound. In the Rottweiler (table 6.6a), the range of stifle joint motion with the Gaitway attached (61.0 ° (SEM 2.6 °)) was statistically significantly greater ($p<0.05$) than the value recorded when the Gaitway was not attached (51.6 ° (SEM 2.4 °)). However, there was a marked difference, although not statistically significant, between the mean maximum flexion of the stifle joint when the Gaitway was attached (101.9 ° (SEM 3.4 °)) and when it was not (110.2 ° (SEM 0.6 °)).

In the Racing Greyhound (table 6.6b), the range of motion of the stifle joint with the Gaitway attached was statistically significantly greater ($p<0.05$) than when it was not attached. As for the Rottweiler, there was a marked, but non significant, difference between the mean maximum flexion angle of the stifle joint when the Gaitway was attached and unattached (109.5 ° (SEM 3.8 °) and 122.3 ° (SEM 1.9 °) respectively).

At trot, (table 6.7a and b), as during walking, there were few statistically significant differences between the mean measured values when the Gaitway was attached and unattached.

In the Rottweiler (table 6.7a), the mean maximum extension of the stifle joint was statistically significantly greater [a] ($p<0.05$) when the Gaitway was attached than when it was unattached. The mean range of stifle joint motion was also statistically significantly greater [b] ($p<0.05$) when the Gaitway was attached compared to when it was not (74.3 ° (SEM 2.8 °) and 62.7 ° (SEM 2.8 °) respectively). The mean range of hock joint motion, and mean maximum hock joint flexion were noticably greater when the Gaitway was attached than when it was not, but they were not statistically significantly different. The mean values for the metatarsophalangeal joint were also noticeably different between the two recording protocols, but the deviations around the mean are large and they are not statistically significantly different.

In the Racing Greyhound (table 6.7b) the sample size was only 3, therefore no statistical analysis was done on this data. However the stifle and hock joint movements showed noticeable differences depending on the attachment of the Gaitway. The mean range of stifle joint motion with the Gaitway attached (69.8 °) was much greater than when the Gaitway was not attached (52.1 °). The mean range of motion of the hock joint, during the gait cycle, was 45.5 ° with the Gaitway attached and only 32.1 ° when it was not.

The foot velocities of the hindfoot, throughout two gait cycles, of one Rottweiler and one Racing Greyhound at walk and trot, calculated from the cinefilm recordings, with and without the Gaitway system attached, are shown in figs 6.8 to 6.11.
Although they show different gait cycles in the same individual, the foot velocity changes during the gait cyles, with and without the Gaitway system attached, are in close agreement.

6.7.3 THE COMPARISON OF NORMAL ROTTWEILER AND RACING GREYHOUND KINEMATIC GAIT PARAMETERS.

Having examined the accuracy of the Gaitway system and its influence on normal locomotion, the walking speed, gait cycle frequency, swing, stance, gait cycle durations, stride length, duty factors and maximum foot velocities in a total of 28 Rottweilers and 28 Racing Greyhounds were recorded.

The total number of gait cycles recorded and analysed by the Gaitway system were;

	Rottweiler		**Racing Greyhound**	
	Walk	**Trot**	**Walk**	**Trot**
Left	190	179	392	300
Right	171	178	362	283
Both	**361**	**357**	**754**	**583**

The mean number of consecutive gait cycles analysed per period of locomotion were;

	Rottweiler		Racing Greyhound	
	Walk	**Trot**	**Walk**	**Trot**
Left	4.6	4.2	6.5	5.9
(SD)	(1.3)	(1.1)	(1.8)	(1.7)
(SEM)	(0.10)	(0.08)	(0.09)	(0.10)
Right	4.5	4.1	6.5	5.9
(SD)	(1.3)	(1.1)	(1.7)	(1.6)
(SEM)	(0.10)	(0.08)	(0.09)	(0.09)
Both	4.6	4.1	6.5	5.9
(SD)	(1.3)	(1.1)	(1.7)	(1.6)
(SEM)	(0.07)	(0.06)	(0.06)	0.07)

The mean values (SD) for the kinematic gait parameters measured by the Gaitway system for both the mature and immature Rottweilers and Racing Greyhounds are shown in tables 6.8 to 6.11. The values for the left, right and both hindlimbs combined for the mean walking speed, gait cycle frequency, stride length, stance, swing and gait cycle durations, duty factor, maximum foot velocity, Froude number and relative stride length are given.

MATURE ANIMALS (tables 6.8 and 6.9)

There were no statistically significant differences between the mean values recorded for the left and right hindlimbs, in either breed, at walk or trot.

At walk, table 6.8, the mean walking speed of the Rottweiler was not statistically significantly different from that of the Racing Greyhound.

The mean gait cycle frequency was statistically significantly greater [a] ($p<0.001$) in the Rottweiler compared to the Racing Greyhound.

The Rottweiler had a statistically significantly greater [b] ($p<0.0001$) stride length compared to the Racing Greyhound. The difference between the mean relative stride lengths of the two breeds was also statistically significantly different [h] ($p<0.0001$).

The mean stance phase duration of the Rottweiler (0.39s (SEM 0.01s)) was statistically significantly shorter [c] ($p<0.0001$) than the Racing Greyhound (0.43s (SEM 0.01s)) but there was no statistically significant difference between the mean swing phase durations of the two breeds (Rottweiler 0.42s (SEM 0.01s), Racing Greyhound 0.42s (SEM 0.01s)).

The gait cycle duration of the Rottweiler (0.81s (SEM 0.02s)) was statistically significantly shorter [d] ($p<0.01$) than the Racing Greyhound (0.85s (SEM 0.01s)), and the mean duty factor of the Rottweiler was statistically significantly less [e] ($p<0.001$) than that of the Racing Greyhound.

The mean maximum foot velocity of the Rottweiler was statistically significantly greater [f] ($p<0.05$) than that of the Racing Greyhound.

Finally, at walk, the mean, dimensionless speed parameter, Froude number of the Rottweiler was statistically significantly greater [g] ($p<0.001$) than that of the Racing Greyhound.

At trot, table 6.9, the mean trotting speed of the Rottweiler was statistically significantly greater [a] ($p<0.0001$) than the Racing Greyhound.

The mean gait cycle frequency was statistically significantly more [b] ($p<0.0001$) in the Rottweiler compared to the Racing Greyhound.

The mean stride length was statistically significantly longer [c] in the Rottweiler (1.19m (SEM 0.02m)) compared to the Racing Greyhound (1.04m (SEM 0.02m)), and, as seen at walk, the relative stride length of the Rottweiler (2.11 (SEM 0.02)) was also statistically significantly longer [h] than the Racing Greyhound (1.88 (SEM 0.02)).

As with the walk, the mean stance phase durations of the Rottweiler and the Racing Greyhound during the trot were statistically significantly different [d] ($p<0.001$) but the mean swing phase durations were not. The mean gait cycle durations were statistically significantly less [e] ($p<0.0001$) for the Rottweiler than the Racing Greyhound, as were the duty factors of the Rottweiler compared to the Racing Greyhound.

The maximum foot velocity was statistically significantly greater [g] ($p<0.0001$) in the Rottweiler (4.48m/s (SEM 0.09m/s)) compared to the Racing Greyhound (4.11m/s (SEM 0.06m/s)).

The mean Froude number of the Rottweiler and the Racing Greyhound were not statistically significantly different.

All the mean combined values of the kinematic data records at walk (table 6.8) were statistically significantly different ($p<0.001$ - $p<0.0001$) from the equivalent values at trot (table 6.9) for both the mature Rottweiler and the mature Racing Greyhound.

IMMATURE ANIMALS (tables 6.10 and 6.11)

Because so few individual immature animals were examined (2 Rottweilers and 2 Racing Greyhounds), it would be inappropriate to statistically analyse (t test) these results. Therefore only the trends in the figures will be discussed in this section.

There were no great differences between the mean values recorded for the left and right hindlimbs in either breed, at walk or trot except in the Rottweiler at walk, the mean left and right swing phase durations and the maximum foot velocities were noticeably different.

At walk, table 6.10, the mean walking speed of the Rottweiler was noticeably greater than that of the Racing Greyhound.

The gait cycle frequency (cycles/min) of the Rottweiler was greater than the Racing Greyhound.

The mean stride length of the Rottweiler (0.92m) was greater than that of the Racing Greyhound (0.87m). The relative stride length of the Rottweiler was also greater than that of the Racing Greyhound.

The stance, swing and gait cycle durations of the Rottweiler were all noticeably shorter than those of the Racing Greyhound.

The mean duty factor of the Rottweiler was also less than the Racing Greyhound.
The maximum foot velocities of the Rottweiler (3.56m/s) and the Racing Greyhound (3.27m/s) were similar.
Finally, the Froude number, at walk, was noticeably greater in the Rottweiler compared to the Racing Greyhound.

At trot, table 6.11, as at walk, the mean trotting speed in the Rottweiler was greater than that of the Racing Greyhound.
The mean gait cycle frequency of the Rottweiler was greater than that of the Racing Greyhound.
The stride lengths of the Rottweiler (1.07m) and the Racing Greyhound (1.00m) were similar, but the relative stride lengths of the Rottweiler and Racing Greyhound (2.15 and 1.74 respectively) were more noticeably different.
The stance, swing and gait cycle durations of the Rottweiler were less than those of the Racing Greyhound. Consequently, the duty factor of the Rottweiler was less than that of the Racing Greyhound.
The maximum foot velocity of the Rottweiler was similar to the Racing Greyhound.
The Froude numbers of the Rottweiler were noticeably greater than the Racing Greyhound.
The mean temporal and dimensionless parameters (Froude number and relative stride length) of the immature dogs, at walk, were all noticeably different from those at trot in the same breed, except for the mean swing phase durations of the Rottweiler at walk (0.35s) and at trot (0.35s) which were similar.

6.8 DISCUSSION

The modified Gaitway system has proved a reliable method of recording certain canine kinematic gait parameters.

Because the modified system does not rely on the detection of a period of simultaneous zero velocity in both tapes (double support period), the system can be used to record the trotting as well as the walking gait.

The disadvantages of the modified Gaitway system at present are the incorrect left and right table headings displayed by the microcomputer, and the inability of the system to display the interlaced records of the left and right hindfeet movements on the VDU prior to printing on hard copy. These problems could be corrected by appropriate modifications to the existing software program.

The low intolerance rate (8.3%) of untrained dogs to the system, and the relatively few familiarisation walks required to achieve the recording of a normal gait, mean that the modified Gaitway system has the potential for further investigation of normal and abnormal gait.

The accuracy of the kinematic gait values represented by the modified Gaitway system were compared with the values measured from a simultaneously recorded cinefilm. In both the Rottweiler and the Racing Greyhound, there were no significant differences between the mean speeds of locomotion, stride lengths, foot velocities or gait cycle durations when measured from the cinefilm or by the Gaitway system, at walk or trot. Although the gait cycle durations were approximately the same, the proportion of the period recorded as the stance or swing phase did vary between the two methods of measuring the same gait cycles.

The stance phase duration, as a percentage of the gait cycle duration (duty factor) as measured by Gaitway, was consistently less at walk and trot in both breeds when compared to the duty factor measured directly from the cinefilm. Because the gait cycle durations were similar, it is the determination of the beginning and end of each phase by each method which differ, not an error in the measurement of the actual temporal values.

The stance and swing phase durations measured manually from the time versus distance plots showed that there was no significant difference compared to those recorded from the cinefilm. The position of the tape attachment at the metatarsophalangeal joint resulted in minor tape movement prior to the actual commencement of the swing phase which led to the Gaitway system registering the end of the stance phase prematurely with a negligible effect on the stride length parameter.

Therefore the modified Gaitway system accurately reflects the temporal and spatial events occuring during locomotion, but the division of the gait cycle duration into the stance and swing phases by the Gaitway differs from the direct cinefilm analysis method.

Despite the normal, qualitative appearance of the gaits of the recorded dogs after 4-6 practice walks in 91.7% of cases, the influence of the Gaitway system on the normal gait was quantitatively assessed by walking the same dog with and without the Gaitway attached, and comparing the kinematic gait parameters, both temporal and spatial, measured from the cinefilm in each case.

At walk, in both the Rottweiler and Racing Greyhound, there were no significant influences on the temporal gait parameters or stride lengths when the dogs were walked with the Gaitway attached. The similarity between the stance, swing and gait cycle durations when the Gaitway was attached and unattached, reinforces the statement that the Gaitway system does not affect the temporal gait parameters, and thus the differences seen during the study in its accuracy is purely due to a different interpretation of the beginning and end of the swing and stance phases in the gait cycle (6.7.1).

At trot, there were no differences seen in the Rottweiler with and without the Gaitway attached. In the Racing Greyhound, the gait cycle duration and the gait cycle frequency were noticeably different in the recordings plus and minus the Gaitway, but these differences were due to the difference between the trotting speeds of the recordings rather than any influence of the Gaitway on the normal temporal gait parameters.

The only statistically significant differences between the mean hindlimb joint angle changes with and without the Gaitway attached, were seen in the stifle joint where the joint maximally flexed significantly more when the Gaitway was attached in both breeds at walk and trot. There were also large differences in the maximum flexion of the hock joint with and without Gaitway, but these differences were not statistically significant.

The foot velocity throughout the gait cycle does not appear to be affected by the attachment of the Gaitway system to the hindlegs.

It may be expected that as the stifle joint flexes to a greater degree when the Gaitway system is attached (mean Rottweiler 110.2° to 101.9° (8.3°), mean Racing Greyhound 122.3° to 109.5° (12.8°)) that other gait parameters would also be altered. In fact no other gait parameters, temporal or spatial, were significantly changed.

This is explained by examining the extent of the movement of the lower limbs, especially the footy relative to the ground, either horizontal or vertical, which is required to achieve such angular changes at the stifle joint.

The stance phase plays no role in the altered maximum stifle joint flexion which occurs during the swing phase and the stance phase duration is unaffected by the events in the swing phase.

Using the known mean tibial and femoral lengths and the stifle and hock joint angles the approximate mean distance the hock joint must move towards the hip joint to achieve this extra stifle joint flexion can be calculated trigonometrically (fig. 5.7)

$$s = \frac{t \sin b}{\sin (b + c)}$$

At walk - Rottweiler hock must move approximately 3-4cm towards the hip

Racing Greyhound must move approximately 2-3cm towards the hip

At foot velocities of 4.0 - 4.2m/s (fig. 6.8 and 6.9) the time duration of this movement would be very small - approximately 0.005 - 0.01s

With an interframe time interval of 0.02s no significant temporal parameter difference will be detected (swing phase and gait cycle durations and foot velocity).

The stride length will not be significantly affected by the increase movement of the hock towards the hip because a certain proportion of that movement will be vertical and stride length has a purely horizontal component.

Walking and trotting gaits are natural symmetrical patterns which are unconsciously regular and repeatable. This includes the stride lengths which are unlikely to be affected by the very small horizontal component of the extra hock joint movement towards the hip.

The other hindlimb joint angles were not significantly affected by the attachment of the Gaitway system. As stride length is unaffected it is expected that the pace angle will also be unaffected.

The hock joint did flex to a greater degree when the Gaitway system was attached but not significantly so. This is to be expected as the hock and stifle joints usually follow the same pattern of flexion and extension if not synchronously and to the same degree (fig. 5.16 - 5.19).

Having determined the accuracy of the Gaitway system and its influence on normal locomotion, the temporal and spatial kinematic gait parameters of all those dogs filmed in chapter 5 were recorded with the modified Gaitway system.

The symmetry between the left and right hindlimb movements was again demonstrated, as in chapter 5 with the high speed cinefilm.

Ideally, to compare the kinematic gait parameters of the Rottweiler and Racing Greyhound, the mean speeds of locomotion should be similar. In this series of Gaitway recordings, the mean walking speeds of the two breeds were not statistically significantly different. The mean stride lengths, and more importantly, the relative stride lengths, were noticeably greater in the Rottweiler compared to the Racing Greyhound at walk, in the mature and immature groups. Therefore, the Rottweiler has a longer stride length relative to its hip height compared to the Racing Greyhound at walk. The mean gait cycle frequency and maximum foot velocity were greater and the mean gait cycle duration, stance phase duration and mean duty factor were shorter in the Rottweiler at walk compared to the Racing Greyhound.

Although a greater stride length and relative stride length were also seen in the Rottweiler at trot (table 6.9), the mean trotting speed was also noticeably greater, which will result in the differences seen between the breeds.

In chapter 4 it was stated that an increase in the speed of locomotion is achieved in one of two ways. By decreasing the gait cycle duration and thereby increasing the gait cycle frequency, or increasing the stride length. Therefore for a true comparison of the gait parameters between the two breeds the speeds of locomotion should not be significantly different (as seen at walk).

The mean trotting speed of the Racing Greyhound measured in section 6.6, shown in table 6.5, is similar to that of the Rottweiler in table 6.9. Here the stride length of the Rottweiler is noticeably greater than that of the Racing Greyhound at similar speeds. Therefore at both walk and trot, the mean stride length of the Rottweiler is greater than that of the Racing Greyhound.

Similar trends were seen for the immature groups, but the sample sizes were very small ($n = 2$).

6.9 CONCLUSIONS

1, The modified Gaitway system accurately records certain temporal and spatial kinematic gait parameters at walk and trot.

2, Although accurately recording total gait cycle durations, the interpretation of the beginning and end of the stance and swing phases within the gait cycles, by the Gaitway system, differs from that obtained by manually analysing the cinefilm. This is due to the tape attachment at the metatarsophalangeal joint resulting in minor tape movement prior to the actual commencement of the swing phase causing the Gaitway to register the end of the stance phase prematurely.

3, The attachment of the hole-punched tapes to the dogs' hindlimbs does not significantly affect the gait parameters measured by the Gaitway system. The Gaitway does, however, significantly affect the stifle joint motion during the gait cycle. High speed cinefilm and Gaitway recordings should not take place simultaneously.

4, The stride length and relative stride length of the Rottweilers were greater than the Racing Greyhounds at walk and trot.

5, The hindlimbs of the Rottweilers bear weight for a greater proportion of the gait cycle than the Racing Greyhounds.

6.10 SUMMARY OF CHAPTERS 5 AND 6

The modified Gaitway system complemented the high speed cinematographic method. Although it is possible to determine all the gait parameters measured by the Gaitway system from the cinefilm recording, it is a time-consuming process.
Foot velocities cannot be measured directly from the cinefilm and require the calculation from joint angle measurements taken from the cinefilm. This is a first derivative calculation and is subject to more error than direct measurement.

Joint angle data cannot be determined from the Gaitway system but this study has proved that the system does influence the movement of the stifle joint to some degree during the gait cycle. However, the Gaitway system does not influence those kinematic gait parameters measured directly by the system.

The data recorded by the high speed cinematography and the modified Gaitway system have shown the following;
There is good repeatability of temporal and spatial kinematic gait parameters between different periods of locomotion of the same subject. Also there is static and dynamic symmetry between the left and right hindlimbs of the same subject.

Rottweilers have a greater stride length, both absolute and relative to their limb length, than the Racing Greyhound at walk and trot (see section 6.8 and tables 6.5 and 6.9).

There is a greater range of flexion and extension in the hindlimb joints of the Rottweiler than the Racing Greyhound.

The range of movement of the pelvic line relative to the horizontal (pelvic angle) is greater in the Rottweiler than the Racing Greyhound which implies greater spinal flexion near the end of the swing phase, leading to greater protraction and a longer stride length in the Rottweiler.

The hip joint is more flexed and the stifle joint more extended at foot placement in the Rottweiler compared to the Racing Greyhound.

The hip and stifle joints are more extended at the end of the stance phase in the Rottweiler compared to the Racing Greyhound.

The greater stride length is achieved by greater protraction and retraction angles of the hindlimb at the beginning and end of the stance phase of the gait cycle in the Rottweiler compared to the Racing Greyhound and greater stifle joint extension at foot placement and lift off.

CHAPTER SEVEN

CANINE STIFLE JOINT BIOMECHANICS

"Knowledge of the biomechanical properties of soft biological tissue is essential for the understanding of its physiological function."

Woo et al 1981a

GLOSSARY

(adapted from Woo et al 1990a)

CREEP - A viscoelastic behaviour characterised by a change in strain or deformation of a specimen with time under a constant applied stress.

DEFORMATION - (millimetre - mm) The change in dimensions of a specimen under external loading. (For example; the increase in length of a bone-ligament-bone complex under tensile loading).

ENERGY ABSORBED AT FAILURE (newton.metre - Nm =J) The total energy absorbed by the specimen under tensile loading from zero loading until failure. A structural property, represented by the area under the load-deformation curve up to the point of failure.

HYSTERESIS The area on a load-deformation curve between the tension and relaxation curves. It represents the internal energy loss (mainly converted to heat energy) between the loading and unloading phases.

LINEAR STIFFNESS (newton per millimetre - N/mm) The slope of the load-deformation curve where the curve is most linear. A structural property representing the tensile load required to elongate the specimen by a unit length.

LOAD (newton - N) External force applied to a specimen.

MATERIAL PROPERTIES Tensile properties of the ligament substance, as a material, represented by the stress-strain curve.

NEWTON 1 newton produces an acceleration of 1 ms^{-2} in a mass of 1 kg.

PASCAL 1 pascal = a pressure acting uniformly on an area, which exerts a force of one newton vertically on one metre^2 of the area.

1 pascal = 1 Nm^{-2} 1 megapascal = 1,000,000 pascals

$$\textbf{STRAIN} = \frac{\text{change in specimen dimension under external loading}}{\text{initial dimensions}}$$

STRAIN RATE (percent per second - %/s) The rate at which a specimen is deformed

STRESS (newton per square millimetre - N/mm^2 = 1 MPa)

$$\frac{\text{load in a specimen}}{\text{cross sectional area perpendicular to axis of loading}}$$

STRUCTURAL (MECHANICAL) PROPERTIES The tensile properties of the bone-ligament-bone complex as a structural unit. Represented by the load-deformation curve.

TANGENT MODULUS (megapascal-MPa) The slope of a line tangent to a segment of the stress-strain curve within a specified range of strain.

TENSILE PROPERTIES Describe the behaviour of a material under tensile load.

TENSILE STRENGTH (newton per square millimetre - MPa)

$$= \frac{\text{load at failure}}{\text{original cross sectional area perpendicular to axis of loading}}$$

ULTIMATE LOAD (newton - N) The maximum load that can be sustained by a specimen prior to failure.

ULTIMATE DEFORMATION (millimetre - mm) The maximum deformation that can be sustained by a specimen prior to failure.

ULTIMATE STRAIN (percent - %)

$$= \frac{\text{ultimate deformation}}{\text{initial length of specimen}}$$

7.1 INTRODUCTION

Biomechanics is the study of the motion, deformation and strength of biological materials in response to externally applied loads. Loads are characterised as tensile, compressive, shear, bend or torsional (see glossary) (Woo et al 1990a).
The anatomy, function and mechanisms of injury of the canine CrCL have been discussed in detail in chapter 1 and 2. In summary, the CrCL is intracapsular but extrasynovial and acts reciprocally and passively with the caudal cruciate ligament to maintain joint stability together with the surrounding muscles, collateral ligaments, menisci and osseous geometry. Injury to the CrCLs may be the result of a combination of factors which include forces of normal or abnormal magnitude and/or direction acting on normal and/or abnormal ligaments (section 2.2.2). The contribution of the CrCL to the passive cranial stability of the knee joint at 90° flexion is reported to be 80-86% in man (Piziali et al 1980, Butler et al 1980). The action of the muscles surrounding the stifle joint contribute to the stability of that joint and act both agonistically and antagonistically to the function of the CrCL (chapter 1 and 2). *In vitro*, the dynamic muscle forces acting on the joint are absent (unless they are simulated (Arms et al 1984)) and it has been reported that the cadaver stifle joint shows more mobility than *in vivo* (Amis 1985). Trent et al (1976) found 20° rotation in the cadaver joint but only 9° when walking which implies that the muscles provide the initial joint stability *in vivo*. The work presented studied the 'passive' rather than the 'active' restraints to tibio-femoral displacements. Therefore

the data presented here regarding the stability of the stifle joint should be interpreted with this in mind whether it is work quoted from other authors or original material. Ligaments exhibit non-linear mechanical behaviour which allows the stifle ligaments to maintain normal joint kinematics without sustaining substantial loads or deformations but when abnormally large forces are imposed, they are able to quickly provide additional protection to the joint (Woo et al 1990a). The geometric arrangements of ligament fibres plus the material properties of the fibres and ground substance determine the mechanical behaviour of the structure (Noyes et al 1974a).

A number of variable factors have been shown to affect the biomechanical properties of ligaments and these can be divided into two groups:

7.1.1 SPECIMEN VARIABLES

7.1.1.1 SPECIMEN AGE

Section 2.2.4 described the microscopic, degenerative changes which were seen in older canine CrCLs (Zahm 1965, Vasseur et al 1985). Tkaczuk (1968) showed that, with age, collagen fibres enlarge and hence the ligament water content (associated with the ground substance) decreases. This results in an increased ligament linear stiffness and so the ligament ruptures at a lower strain (Amis 1985). Woo et al (1990a) also demonstrated a decrease in the linear stiffness of the femur-CrCL-tibia complex with age in man (young 226-292N/mm, older 129-199N/mm). The ultimate load at failure has been reported as being higher in younger specimens (in man - Noyes and Grood (1976) - young 1730N, old 730N. Woo et al (1990a) found the ultimate load 3 times greater in the young compared to the old, Vogel (1978). In contrast, Kennedy et al (1976) and Alm et al (1974) reported no correlation between age and the ultimate load. But they also reported lower strengths, showing that their test methods caused premature failures (Alm et al 1974 - 665N). Maximum stress (tensile strength), tangent modulus and ultimate strain have all been shown to decrease with increasing age in man (Noyes and Grood 1976). Skeletal maturity is also an important factor as most immature specimens fail either by tibial avulsion or, more commonly, by femoral epiphyseal separation (Amis 1985).

7.1.1.2 CADAVER BODY WEIGHT

Some authors report that the tensile strength of the CrCL is related to body weight (Smith 1954 - rabbit, Gupta et al 1971 - canine), others say it is not (Viidik et al 1965 - rabbit, Alm et al 1974 - canine).

7.1.1.3 SYSTEMIC DISEASE

Collagen disease, such as Ehlers-Danlos Syndrome, and some inflammatory arthropathies may affect the properties of ligaments although there is no biomechanical evidence available. The effects of most other systemic diseases on collagen, in general, and ligaments, in particular, are unknown.

7.1.1.4 STIFLE JOINT INJURIES

Previous stifle joint injuries, whether soft tissue or skeletal may lead to ligament abnormalities. Specimens from such cases should not be used in ligament testing procedures.

7.1.1.5 ACTIVITY

As an extreme of inactivity, a period of immobilisation of the hind limb has been shown, in primates, to significantly weaken the CrCL (39% decrease), decrease the energy absorbed at failure (32% decrease) and increase the ligament extensibility (Noyes et al 1974a and b). Histological changes at the bone-ligament junction have also been demonstrated (Noyes 1974b). Laros et al (1971) reported periosteal bone resorption and a decrease in the ultimate load of the medial collateral ligaments in caged dogs. Viidik (1968) showed that the CrCL in trained rabbits had greater ultimate loads, deformations at failure, energy at failure and linear stiffness than the untrained rabbits. Cabaud et al (1980) also found that exercise increased the ultimate load and linear stiffness of the CrCL. In contrast, Woo et al (1981a) found that training augmented the strength of the insertion site of porcine digital flexor tendons, but had minimal effect on the tendon substance. Mechanical stimulation has been reported as being important for the integrity of ligament, tendon and bone (Viidik et al 1966, Laros et al 1971, Noyes et al 1974b).

7.1.1.6 SPECIMEN DEHYDRATION

In vivo the stifle joint is protected from dehydration by the surrounding muscles and skin and the perfusion and bathing of the local structures with blood, lymph and synovial fluids. From death until the final biomechanical test is completed, the stifle joint is subject to dehydration. Dehyration has been shown to adversely affect the biomechanical properties of connective tissue (Tkaczuk 1968). The decrease in water content will result in an increase in linear stiffness and ligament rupture at a lower strain (Amis 1985), a similar process to ageing. Therefore it is important that any preparation of the limb prior to storage does not penetrate the joint capsule and during testing, especially when the intra-articular structures are exposed, that the joint is repeatedly irrigated with isotonic saline.

7.1.1.7 SPECIMEN STORAGE

It is not always possible to prepare and biomechanically test cadaver material immediately after death and therefore a simple method of storage which does not affect the properties to be tested is required. Although it has been reported that the tensile properties of intra-articular ligaments are unaffected 96 hours post mortem at room temperature (Viidik 1965, Viidik and Lewin 1966), histological changes are seen 2 hours after death where collagen bundles become swollen, then after 24 hours the nuclei begin to disintegrate (Viidik et al 1965). Smith (1954) reported that 1 hour post mortem the CrCL becomes less extensible, that is, the tangent modulus of the ligament substance increases. Viidik and Lewin (1966) reported that storage in formaldehyde reduces the tensile strength of ligaments but that storage in blood plasma or synovial fluid was ideal. Deep freezing at minus 18-30 degrees Celsius (^{o}C) is the most widely used method of storing collagenous material (Viidik et al 1965, Viidik and Lewin 1966, Bingham et al 1979, Vasseur et al 1985, 1991, Woo et al 1986, Butler et al 1990, Mabuchi et al 1991). Provided that dehydration is prevented (Tkaczuk 1968), freezing is reported to have minimal effects on the biomechanical properties of ligaments. Viidik et al (1965) recorded no effect on the load-deformation curve, ultimate load and deformation and only a slight reduction in the energy at failure in rabbit ligaments. Sedlin and Hirsch (1966) reported no effect of storage at minus 20^{o}C on ligaments, Noyes and Grood (1976) found no effect on human and monkey ligament biomechanics or cross sectional areas, Dorlot et al (1980) reported an increase in ligament linear stiffness but no effect on its strength, Mabuchi et al (1991) found no effect of freezing on ligament linear stiffness, Woo et al (1986) found no statistically significant differences in the load-deformation curve, ultimate load, deformation, energy at failure, stress/strain, tensile strength or ultimate strain in rabbit medial collateral ligaments stored at minus 20^{o}C, although he found the area of hysteresis was significantly reduced in the first few loading and unloading cycles.

7.1.2 EXPERIMENTAL VARIABLES

7.1.2.1 TEMPERATURE

Ligaments exhibit temperature-dependent mechanical properties (Woo et al 1987b). Dorlot et al (1980) reported that temperatures from 22^{o}-45^{o}C had no effect on the behaviour of canine CrCLs. In contrast, Walker et al (1964) showed that over a temperature range of 23^{o}-$49^{o}C$, the linear stiffness of the canine Achilles and patellar tendons significantly decreased, Kuei et al (1976) found similar effects in porcine lateral collateral ligaments at 22^{o}-$37^{o}C$. Woo et al (1987b) showed that the area of hysteresis decreased with increasing temperature over a range of 2^{o}-$37^{o}C$ in canine medial collateral ligaments and the tensile load at a set ligament strain level was inversely proportional to the ambient temperature. Therefore all the biomechanical testing of different specimens should take place at similar ambient temperatures to reduce the effects of temperature on the biomechanical properties of ligaments.

7.1.2.2 MOUNTING THE FEMUR AND TIBIA IN THE MATERIALS TESTING MACHINE

The specimen must be firmly fixed in the mountings of the machine as slippage will result in errors in the load-deformation curves which will lead to errors in all the biomechanical properties measured and calculated from those curves.

7.1.2.3 TESTING PROTOCOL

A number of factors in the positioning and testing protocol of the specimen in the materials testing machine have been shown to influence the measurement of the biomechanical properties of ligaments and many of these factors are inter-related. They include loading axis, magnitude of loading, deformation (strain) rate of the joint specimen, angle of the joint, angle of tibial rotation, compressive loading and muscle action.

LOAD AXIS The axis of loading is reported to have significant effects on the properties of ligaments. Past studies have most commonly tensile loaded the stifle joint ligaments along the ligament axis or along the tibial axis. The results of studies which have compared the two loading axes are in general agreement. Ligament linear stiffness, energy at failure, area of hysteresis, ultimate deformation and ultimate loads have all been reported to be greater when loaded along the ligament axis compared to loading along the tibial axis (Amis 1985 - rabbit CrCL, Woo et al 1987a, Woo et al 1990a - rabbit CrCL, Lyon et al 1989 - pig CrCL). The mode of failure of the CrCL is also affected by the loading axis, tibial axis loading resulted most commonly in tibial plateau avulsion, ligament axis loading in ligament substance failure (Amis 1985).

MAGNITUDE OF LOADING During cyclic craniocaudal loading to measure the craniocaudal stability of the joint, the greater the load, the greater the deformation of the tibia relative to the femur. Ligaments exhibit elastic properties over a certain range of loading and will return to their original length when they are unloaded. If the load is too great, the ligament will enter a plastic phase and will be permanently damaged at a microscopic level, usually as the result of collagen fibres shearing on one another rather than rupturing (Smith 1954) and the ligament will not return to its original, unloaded state. The reported percentage strains (deformation of the ligament divide by the original ligament length x 100) at which ligaments are permanently damaged range from 14% (Dorlot et al 1980) to 20% (Smith 1954).

Therefore the maximum load applied to the stifle joint when testing its craniocaudal stability should not result in a percentage strain greater than 14%.

DURATION OF LOADING Ligaments exhibit time-dependent properties. Loads applied to the ligament for different times will produce different elongations due to visco-elastic behaviour and creep (Amis 1985). This is only significant at sustained high loads.

JOINT ANGLE There is no generally recognised convention as to how the angle of a joint is expressed. It may be presented either as the internal (extension) angle between the long axes of the femur and the tibia, or as the flexion angle which is when the femur and tibia are in a straight line, the flexion angle is 0^{o} flexion and as the hip and hock joints move closer together, the flexion angle increases.

Ie. Extension angle 150^{o} = Flexion angle 30^{o}.

In this study, the former convention is used.

The angle at which a stifle joint is tested has been shown to affect some biomechanical properties in some studies. Lyon et al (1989) reported that the ultimate load of porcine CrCLs were not affected by the joint angle when they were loaded along either the ligament or tibial axes, but linear stiffness decreased as the joint angle decreased in tibial axis loading. In contrast, Woo et al (1987a) showed that the ultimate load decreased with a decreasing stifle joint angle (180^{o}- 90^{o}) when loaded along the tibial axis. The stifle joint angle had no effect on the ultimate load when the ligament was loaded along the ligament axis (Woo et al 1987a). They also found that ultimate deformation decreased with decreased joint angle when the ligament axis was loaded but there was no effect on the energy at failure. Figgie et al (1986) also found that tibial axis loading decreased the ligament ultimate load with decreasing joint angle and at 90^{o}, the CrCL had only 40% of the ligament strength recorded at full extension. The modes of ligament failure also varied with the loading axis. Tibial avulsion occured more frequently when loaded along the ligament axis (Woo et al 1987a, Lyon et al 1989). Craniocaudal stability in the intact stifle joint increases with increasing stifle joint angle. Many studies have not detailed the loading axes at testing and so results are difficult to compare (Viidik et al 1965, Viidik and Lewin 1966, Gupta et al 1969, 1971, Noyes et al 1974a, Dorlot et al 1980).

AXIAL TIBIAL ROTATION Alm et al (1974) reported that the tensile strength of the canine CrCL tested at a stifle joint angle of 90^{o} was greatest when the tibia was fixed in neutral tibial rotation, which they described as being the canine stifle joint's anatomically normal position. They noted that 15^{o} of tibial rotation resulted in a 15% decrease in the tensile strength of the CrCL compared to its strength at neutral tibial rotation. The CrCL twists approximately 90^{o} between its femoral origin and tibial insertion (see chapter 1) with the ligament fascicles running helically around the ligament (Stouffer et al 1983). This results in a torque moment always accompanying the tensile load during deformation of the ligament (Butler and Stouffer 1983, Stouffer et al 1983). As a tensile load is applied to the ligament, it deforms and the accompanying torque moment results in the tibia rotating internally relative to the femur (Stouffer et al 1983). In man, when a cranial drawer force is applied, the tibia rotates up to 10^{o} (Fukubayashi et al 1982). They also reported an increase in the craniocaudal deformation of 30% when the tibia was able to rotate freely compared to when the tibia was fixed in neutral rotation. Kennedy et al (1980) showed that greater forces were needed to produce small deformations when the tibia was fixed. Some other reports also tested the ligament biomechanical properties at neutral rotation (Viidik 1968, Gupta et al 1969, Noyes et al 1974a, Noyes and Grood 1976, Butler et al 1980, Butler and Stouffer 1983, Butler et al 1983, Dorlot et al 1980, Lyon et al 1989, Vasseur et al 1991, Amis et al 1992). Others allowed the CrCL to unwind prior to the measurement of the ligament dimensions and biomechanical testing (Gupta et al 1971, Kennedy et al 1976, Bingham and DeHoff 1979). Gupta et al (1969, 1971) found no statistically significant differences in the tensile strengths of the canine CrCL which were tested in a normal, anatomical position and those which were untwisted prior to testing. Drouin et al (1981) found no significant differences in linear stiffness between the twisted and untwisted ligament preparations.

COMPRESSIVE LOADING OF THE STIFLE JOINT AND MUSCLE ACTION

Compressive loading occurs during weight-bearing and is reported to decrease the load on the CrCLs (Lewis et al 1989) and so act as a protective mechanism that avoids ligament strain. Joint compression is also reported to increase the craniocaudal, mediolateral and varus/valgus stiffness of the joint and decrease the joint craniocaudal and rotatory laxity (Wang and Walker 1974, Hsieh and Walker 1976, Markolf et al 1981), although the collateral ligaments are said to be twice as important in resisting joint rotatory laxity as the cruciate ligaments (Wang and Walker 1974).

DEFORMATION RATE OF THE JOINT SPECIMEN Noyes et al (1974a) (deformation rates 0.084mm/s and 8.46mm/s) and Kennedy et al (1976) (2.08mm/s and 8.31mm/s) studied the effects of slow and fast deformation rates on the biomechanical properties of monkey and human CrCLs respectively. They both found that the ultimate load increased as the deformation rate increased. Noyes et al (1974a) reported that the ultimate load increased by 21% as the test speed increased one hundred fold. They also reported that the ultimate deformation and energy to failure also increased by 15% and 31% respectively with the increased deformation rate. The CrCL absorbed more energy at the higher deformation rate and so required a greater load to fail it (Kennedy et al 1976). Linear stiffness is reported by some authors to increase with increasing deformation rates up to 10mm/s (Haut and Little 1969, Noyes et al 1974a) but is said not to be affected at higher deformation rates of 100-1000mm/s (Mabuchi et al 1991). The modes of CrCL failure were also affected. As the deformation rates increase, more ligament substance failure and less tibial avulsion has been reported (Noyes et al 1974a, Cabaud et al 1980). This is said to be due to an increase in the strength of the bony insertions of the ligaments at the higher loading rates (Noyes et al 1974b). Bone will withstand approximately two times the stress at higher rates of deformation than at lower rates. Because most CrCL ruptures seen clinically occur mid-substance, this implies that joint injuries occur rapidly and from this, testing to ligament failure should be carried out at high deformation rates to mimic the physiological CrCL rupture mechanism.

Ligament strain is the deformation of the ligament or section of the ligament under load divided by the original ligament or section of ligament length. In many cases the displacement of the tibia relative to the femur during loading, divided by the original measured length of the entire ligament, is used to represent the ligament strain (Gupta et al 1971, Noyes and Grood 1976, Lyon et al 1989, Vasseur et al 1991). Ideally, however, the CrCL strain, which is non-uniform as loading does not occur along the length of all the CrCL fibres, should be measured along a specific area of the ligament substance and not across the bone-ligament-bone complex as a whole, although this is not always possible. A number of different methods have been used to determine the strain in the CrCL in the intact joint; radiographs (Wang and Walker 1974, Bartel et al 1977), strain gauges (Kennedy et al 1977), buckle transducers (Paulos et al 1981, Lew et al 1982, Ahmed et al 1984, Sidle et al 1988), buckle transducer plus a 6 degree of freedom goniometer (Lewis et al 1989), Hall's transducer (Arms et al 1984), 6 degrees of freedom spatial linkage (Hefzy and Grood 1986, Butler et al 1988, Lewis et al 1988, Suntay et al 1988). Woo et al (1983) used three horizontal lines of Verhoff elastic stain on the ligament as an initial gauge length and recorded the change in length upon loading with a video dimensional analyser. He found that the ligament substance strain was consistently less than the deformation of the bone-ligament-bone complex and suggested that the ligament stretch was non-uniform with a high deformation at the ligament-bone junction.

The degree of strain in the CrCL in man over the range of stifle joint angle movement from 180^{o}-120^{o} was reported to depend on whether the change in the joint angle was achieved passively or actively by contraction of the quadriceps muscle group. The strain in the CrCL was significantly higher when the quadriceps were active to change the joint angle (Arms et al 1984).

7.1.3 AIMS OF BIOMECHANICAL TESTING

The aim of this section of the project was to test the craniocaudal stability of the stifle joint and to measure the structural and material properties of Rottweiler and Racing Greyhound cadaver CrCLs *in vitro*. In chapter 5, the angular fluctuations of the stifle joint throughout the gait cycle in normal Rottweilers and Racing Greyhounds at walking and trotting gaits were determined using high speed cinematography. The mean range of stifle joint angular movements in each breed were used to decide the joint angles at which the craniocaudal stability testing would occur (Rottweiler 160^{o} -110^{o}, Racing Greyhound 150^{o}-110^{o}). The angles of the stifle joint used to test the ligaments to failure were the mean minimum and maximum degrees of flexion exhibited by the stifle joints during the stance phase of the gait cycle (Rottweiler 160^{o}-130^{o}, Racing Greyhound 150^{o}-130^{o}).

For the following series of biomechanical tests on cadaver stifle joints, no attempt was made to simulate active muscle action and the joint was subjected to shear or tensile loading only, no compressive loads were used.

Although the factors which influence the biomechanical properties of ligaments are numerous, wide-ranging and frequently inter-related as described above, it is important to appreciate the degree to which they can influence the results of biomechanical tests. Limiting the effects of these factors by appreciating their presence and striving to reduce the variability of the specimen population and the experimental methods, as well as thoroughly documenting the procedures used, allows the standardisation of testing, the consistency of results and the ability to compare results with those of other studies.

7.2 CADAVER STIFLE JOINT PREPARATION

Cadaver hindlimbs were collected, prepared and stored (by freezing at -18 degrees Celsius) over a period of 15 months. A total of 26 Rottweiler (13 pairs) and 30 Racing Greyhound stifles (15 pairs) were obtained. The donor animals were euthanased by an overdose of intravenous barbiturates, for reasons other than this study. The ages and previous history of most of the donor dogs were unknown, although all the dogs appeared young.

	Rottweiler	**Racing greyhound**
	(n = 26)	(n = 30)
Male (%)	72.7	63.6
Female (%)	27.3	36.4
Mean weight (kg)	41.7	31.8
Standard Deviation (SD)	(3.0)	(3.2)
Standard Error of Mean (SEM)	(0.91)	(0.95)

The hindlimbs were disarticulated at the hip joint. The skin was removed from the limbs together with all the soft tissues (muscular, neurovascular and adipose tissue) except for an area 3-4 cm proximal and 3-4 cm distal to the stifle joint line. The distal quadriceps tendon, patella and straight patellar tendon were left *in situ* and the joint capsule, collateral ligaments and the stifle joint intra-articular structures remained intact.

Lateral radiographs of all the stifle joints were taken to ensure the specimens were skeletally mature (closed epiphyses) and to help identify the presence of any disease in the specimens which would have excluded them from the study. None was found.

7.3 SPECIMEN STORAGE

Following the soft tissue removal, the hindlimbs were wrapped individually in gauze, soaked with isotonic saline to prevent any dehydration of the specimens which adversely affects the biomechanical properties of connective tissue (Tkaczuk 1968). They were placed in individual, air-tight polyethylene bags and stored at minus 18 degrees Celsius until testing. This method of storage has been reported to have minimal effects on ligament biomechanics (Viidik et al 1965, Sedlin and Hirsch 1966, Noyes and Grood 1976, Dorlot et al 1980, Woo et al 1986). The period of storage ranged from 4 to 15 months. The time from euthanasia to freezing of the prepared hindlimb ranged from 3 to 6 hours.

7.4 MOUNTING THE SPECIMEN FOR TESTING

At the time of biomechanical testing the specimens were thawed, as required, by placing them in a warm water bath and then, upon removal from the water, allowing them to equilibrate to room temperature prior to testing. It was important to let the specimens reach room temperature as the biomechanical properties of the CrCL are temperature-dependent (Kuei et al 1976, Walker et al 1976, Woo et al 1987b). It was not possible in these experiments to test the stifle joint biomechanical properties at body temperature, therefore making sure that the stifle joint specimens were equilibrated to room temperature at least, resulted in all the ligaments being tested as near to the physiological norm as possible. The specimens were kept sealed in the air-tight polyethylene bags until immediately prior to testing to prevent them absorbing water from the water-bath which would affect their biomechanical properties (ligament intercellular ground substance is hydrophilic) (Viidik and Lewin 1966, Tkaczuk 1968) and to reduce the risk of dehydration before the specimens were mounted in the materials testing machine.

The remaining bulk of the soft tissues was carefully removed, still leaving the joint capsule, collateral ligaments, patella and straight patellar ligament intact. The femoral and tibial shafts were cut, with a junior hacksaw, leaving a length of each bone of approximately 6-7 cm to mount in the materials testing apparatus. To optimise the grip of the specimen in the mountings, the periosteum was removed from the femoral and tibial shafts which were then degreased with alcohol. Small notches were made in the shafts with a rasp.

Both femur and tibia were mounted in separate stainless steel cylinders, each of which had 3 screws to centralise and help hold the bones in position whilst polymethylmethacrylate bone cement[a] was poured into the cylinders and allowed to harden over approximately 20-30 minutes. The femur was mounted toward the front of its steel cylinder and the tibia toward the back to reduce the likelihood of the upper mounting impinging on the lower during the tests at the greatest stifle joint angles (150^{o}-160^{o}). The solid bone cement surrounding the 3 cylinder screws and the roughened bone shafts resulted in a firm fixation of the bone ends in the stainless steel cylinders (fig. 7.1). The specimens were embedded as near to the joint as possible without allowing the bone cement to contact the collateral ligament attachments, as the chemical reaction resulting in the bone cement hardening is moderately exothermic and temperatures above 45 degrees Celsius will denature protein (a constituent of collagen) and so adversely affect the biomechanical properties of the specimen to be tested. Whilst preparing the bone cement, care was taken to minimise the amount of air introduced into the liquid during mixing because the exothermic reaction during the solidifying process warms the trapped air and results in expansion of the bone cement which may partially engulf the joint specimen and may also result in the solid cement being weaker than normal.

Throughout the following biomechanical testing procedures the joint preparations, whether intact or joint capsule-deficient, were prevented from dehydrating by frequent irrigation of the joint with isotonic saline.

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[a] Austenal Dental Simplex Rapid - self curing. Associated Dental Products, Kemdent Works, Purton, Wiltshire, England.

" The tight stifle joints of quadrupeds depend on cruciate stability to a greater extent than does the human knee, which has more secondary restraints."

Amis et al 1992

7.5 CRANIAL-CAUDAL STABILITY TESTING

The stifle joint preparation, fixed in the steel cylinders, was mounted in an Instron 1122 materials testing machine. The femur was placed in a rigid holder attached to the base of the machine whose angle could be changed to alter the angle of the femur relative to the tibia. Once the bolts of the femoral mounting were tightened, the femur was unable to move in any direction, craniocaudal, mediolateral or rotatory. The tibia was suspended horizontally in the upper moving crosshead attached to a load cell (fig 7.2). The tibial suspension mechanism had a series of linear and rotatory bearings which allowed free tibial motions with 4 degrees of freedom of motion - varus/valgus rotation, internal/external rotation, medial/lateral translation, proximal/distal translation (fig 7.2). This specialised mounting prevented the femoral condyles from ploughing into the tibial plateau (Amis 1989, Amis and Scammell 1993) leading to unphysiological compression caused by apparatus constraints (Fukabayashi et al 1982). Noyes et al (1980) used a rig with 1 degree of freedom. In earlier work, a small distraction force was added when the tibia was clamped to stop the femoral condyles impacting on the tibia (Amis 1989).

Free tibial internal and external rotation was achieved by having the tibial cylinder mounted in a freely rotating inner-tube lining the main suspension mechanism. By tightening a screw on the outer casing, the tibial mounting could be prevented from rotating internally or externally without affecting the other free tibial movements (fig 7.3).

Manipulation of the femoral and tibial mountings allowed the load axis of the materials testing machine to be directed through the joint. The joint was initially unloaded and in neutral (mid-tibial) tibial rotation prior to testing (Amis et al 1992). To obtain the neutral, unloaded starting position, the joint specimen is cycled 2-3 times and the inflection point of lowest stiffness as seen on the load-deformation curve (fig 7.4) was found.

An integral graph plotter, attached to the Instron machine, recorded the vertical displacement of the moving upper crosshead relative to the fixed lower mounting as a function of the tensile load applied by the load cell. The graph plotter was calibrated so that the full scale deflection load, that is, the load recorded by the entire width of the graph paper represented 500N. With the stifle specimen mounted in the Instron machine, the load controls were set with the pen recorder in the centre of the paper and the upper crosshead was programmed to move vertically at a rate of 50mm/min in one direction to a load of 100N and then to automatically reverse to a load of 100N in the opposite direction. The paper speed in the graph plotter was set at a ratio of 5:1, which meant that five small divisions on the recording paper (10mm) corresponded to an actual crosshead displacement of 2mm. The Instron machine was programmed to load to a maximum of 100N because this load is not so great that it will irreversibly stretch the ligament but it is greater than the loads which are applied manually during a cranial drawer test (45-85N) and so it will test the craniocaudal stability of the joints to a greater degree.

7.5.1 TEST PROTOCOL

Before recording the craniocaudal stability of each joint specimen, either intact or when only the CrCL remains, the bone-ligament-bone preparation underwent 3 loading and unloading conditioning cycles. The 4 subsequent cycles were recorded. Loading of the joint in this setup resulted in the testing of the craniocaudal stability of the joint similar to, but at a greater tensile load, than the cranial drawer test.
Each stifle preparation was tested at a number of different joint angles in neutral tibial rotation. At each joint angle, four different craniocaudal stability procedures were carried out.

1) 4 x loading-unloading cycles of the intact joint with the tibia able to rotate freely internally or externally.

2) 4 x loading-unloading cycles of the intact joint with the tibia fixed in neutral rotation and unable to rotate freely.

At this point, all of the soft tissues, except the CrCL, were removed taking care not to damage the ligament's origin and insertion when the menisci were removed. The tissues removed were joint capsule, collateral ligaments, caudal cruciate ligament and menisci. Dorlot et al (1980) left the menisci *in situ* as he claimed that removal would damage the ligament insertions.

3) 4 x loading-unloading cycles of the joint with only the cranial cruciate ligament intact and the tibia able to rotate freely.

4) 4 x loading-unloading cycles of the joint with only the cranial cruciate ligament intact and the tibia fixed in neutral rotation (ie. unable to rotate freely).

Throughout this study, 180 degree joint angle represents the position where the tibia and femur are in a straight line relative to one another and not where the stifle joint is at its full extension which may be 160-165^{o} from the tibia and femur being aligned in a straight line as reported by some authors (Oster et al 1992).
Two series of Rottweiler and Racing Greyhound stifle joints were tested with slightly different test protocols.

SERIES 1

7 Rottweiler stifle joints were tested at 160, 140, 130, 110 degrees.
6 Racing Greyhound stifle joints were tested at 150, 130, 110 degrees.
These joint angles for each breed were determined from the high speed film analysis of normal walking and trotting gaits described in chapter 5. The physiological

maximum extension angle was tested and then 2 or 3 other angles of greater joint flexion.

In this series when the Instron mountings were moved, to allow the testing of the intact joint at different angles, no record was kept of the exact position of the mountings. Therefore when the tests were repeated at the same angles but with only the CrCL intact, it was not possible to return the mountings and therefore the joint to the exact setup as for the intact joint. Thus there could be no direct comparison between the load-displacement curves of the intact and CrCL-only joint in series 1.

In this series, 16 and 12 craniocaudal stability tests were carried out on each Rottweiler and Racing Greyhound stifle joint respectively.

SERIES 2

3 Rottweiler stifle joints were tested at 160, 150, 140, 130, 110 degrees. One was tested at 130 degrees only and one at 160 degrees only.

4 Racing Greyhound stifle joints were tested at 150, 140, 130, 110 degrees. One was tested at 130 degrees only and one at 150 degrees only.

A similar protocol was used as in series 1 only the exact position was recorded of the mountings at each angle tested for the intact joints so they could be exactly duplicated to re-test the CrCL-only joint. Thus a direct comparison of the intact and CrCL-only load-displacement curves could be made and the contribution of the CrCL to the cranial joint stability could be measured (fig 7.13a). From the load-deformation curve of each intact and CrCL-only specimen, the load at which the CrCl-only specimen achieved the same deformation caused by 100N loading in the intact joint was the contribution of the CrCL to the cranial stability of the joint.

Also, an additional joint angle for both Rottweiler (150 degrees) and Racing Greyhound (140 degrees) was tested in this series.

In this series, 20 and 16 craniocaudal stability tests were carried out on each Rottweiler and Racing Greyhound stifle joint respectively.

Any errors in the recorded craniocaudal displacement values due to a bending deviation of the femoral and/or tibial bones are considered negligible. Firstly, because the bodies of both bones are deeply embedded in solid bone cement within the rigid stainless steel cylinders and only the most distal femoral and proximal tibial areas are visible (fig 7.1), any bending moment tending to deviate the bones will be small. Secondly, the forces used for the craniocaudal stability testing (100N maximum) are relatively small compared to the normal physiological forces on these bones. Therefore the recorded vertical displacements of the moving upper cross head relative to the stationary lower femoral mounting represents the true vertical movement of the tibia relative to the femur. Bingham and DeHoff (1979) believed that bone deformation contributed only 5% to the total deformation recorded.

Statistical analysis of the data collected consisted of the two-sample Student's t-test and the paired Student's t-test. Both t-tests assumed an equal variance in the data.

7.5.2 RESULTS

Radiographically, all of the cadaver specimens were skeletally mature with closed epiphyses.

None of the collected stifle joints had radiographic evidence of joint disease.

An incidental radiographic finding was that the apex of the Rottweiler patella had a boney point, almost a hook or spur, which was seen consistently in all the specimens and was therefore considered to be a normal feature of the Rottweiler patella.

In this study the length of each CrCL was taken as the average between the length of the craniomedial and caudolateral portions of the ligament (Vasseur et al 1991)(see section 7.7.1).

The lengths of the CrCLs in both breeds were measured prior to testing a different set of stifle joint specimens to ultimate failure when the joint was loaded along the ligament axis, and will be described later in this chapter (section 7.8.3).

Although the CrCL lengths of those specimens in series 1 and 2 were not measured, the mean values of all those which were measured (Rottweiler n=7, Racing Greyhound n=9)in group 2 were used to calculate the approximate strain rate during the craniocaudal stability testing.

Mean CrCL length	Rottweiler	= 18.7 mm (0.7 mm SEM)
	Racing Greyhound	= 18.2 mm (0.2 mm SEM)

Strain rate is the rate at which a specimen is deformed (in this case - tensile-loaded), by the application of a tensile force expressed as strain per unit time.

cross head speed = 50mm/min = 0.8mm/s

$$\text{Strain rate} = \frac{\text{displacememt rate mm /s}}{\text{original ligament length mm}} \text{ X 100 percent /second}$$

$$\text{Mean strain rate for Rottweiler stifles} = \frac{0.8\text{mm / s}}{18.7\text{ mm}} = 4.3\% / \text{s}$$

$$\text{Mean strain rate for Racing Greyhound stifles} = \frac{0.8\text{mm / s}}{18.2\text{mm}} = 4.4\% / \text{s}$$

These strain rates are similar to those used in other studies (Hubbard and Chun 1988 5%/s).

A diagram representing the load-displacement curve of a normal canine stifle is shown in fig 7.4. The load-displacement curve of the CrCL during loading and unloading is shown in the top right quarter, and the caudal cruciate ligament is represented by the bottom left quarter. When only the CrCL is intact, there is no curve in the lower half of the graph as there is no caudal cruciate ligament from which a tension curve can be recorded. Hysteresis, the area between the tension and relaxation curves, represents the internal energy loss (mainly converted to heat energy) between the loading and unloading phases. Woo et al (1987b) showed that the area of hysteresis decreased with increasing temperature (2^o-37^oC) and that in those specimens which had been stored at minus 20^oC the area of hysteresis is significantly lowered in the first few cycles (Woo et al 1986) (see section 7.1.1.7).

The load-displacement plots in fig 7.5-7.8a and b represent the mean tension curves of the intact joints of series 1 and 2 and the CrCL-only joints in series 2 described above. The relaxation curve for each plot has been omitted to simplify the load-displacement representations.

The displacement of the tibia relative to the femur every 10N of tensile loading was measured from the individual curves for each specimen at each joint angle. The mean values were calculated and are illustrated in fig 7.5-7.8a and b. Fig 7.7 shows the mean tension curves of intact joints comparing the two breeds at the same joint angle. The mean tension curves of the CrCL-only joints from series 2 at different joint angles are shown in fig 7.8a and b. The maximum cranial displacements at 100N cranial tensile loading were measured from the load-displacement curves at each angle for each individual stifle joint in series 1 and 2, both when the tibia was free to rotate from its initial neutral rotation position, and when it was fixed in neutral rotation. The mean values (Standard deviation SD and Standard Error of Mean SEM) are shown in table 7.1 and fig 7.9. The same was done for the total cranio-caudal

displacement when the joint was loaded from -100N to +100N, table 7.2 fig 7.10. The mean (SD and SEM) maximum cranial displacement for the intact and CrCL-only joints in series 2 at different joint angles are shown in table 7.3 and the mean maximum cranial displacement of the CrCL-only joint as a function of stifle joint angle is illustrated in fig 7.11. Fig 7.12 is a scatter plot of the total craniocaudal displacement of individual stifle joint specimens as a function of the joint angle. The percentage contribution of the CrCL to the cranial stability of individual Rottweiler (n = 3) and Racing Greyhound (n = 3) stifle joints is shown in table 7.4.

CRANIO-CAUDAL STABILITY OF THE INTACT STIFLE JOINT - SERIES 1 AND 2

Figures 7.5 and 7.6 show that the mean load-displacement curves of intact canine stifle joints varied with the angle of the joints at testing when the tibia was able to rotate freely. As the joint was flexed, craniocaudal stability decreased in both breeds, although from the slope of each curve and the comparison of the two breeds at the same joint angle (fig 7.7), the Rottweiler stifle was more lax craniocaudally than the Racing Greyhound at all the recorded joint angles. The mean total craniocaudal displacements for each breed at each joint angle (table 7.2, fig 7.10) also show the increased craniocaudal laxity of the intact joint with increased joint flexion in each breed. With the tibia able to rotate freely, the mean total craniocaudal displacement of the intact Rottweiler joint increased from 3.14mm (SEM 0.54mm) at 160^{o} joint angle to 5.80mm (SEM 0.71mm) at 110^{o}. In the Racing Greyhound, the increase in the mean total craniocaudal displacement was from 1.81mm (SEM 0.28mm) at 150^{o} to 3.59mm (SEM 0.25mm) at 110^{o}. These trends of increased craniocaudal laxity with increased joint flexion and the greater laxity in the Rottweiler stifle joint compared to the Racing Greyhound are illustrated in fig 7.5-7.7. The scatter plot (fig

7.12) shows the total craniocaudal displacement of individual specimens and illustrates a regression coefficient of determination showing positive correlations between the total craniocaudal displacement and the degree of joint flexion of $r^2 = +0.834$ for the Rottweiler and $r^2 = +0.987$ for the Racing Greyhound. Despite the greater Rottweiler stifle joint laxity, the actual mean increase in craniocaudal displacement in the Rottweiler specimens between 150° and 110° flexion was only 1.54mm (5.80mm - 4.26mm see table 7.2) which was similar to the mean increase, over the same joint angle range, seen in Racing Greyhounds - 1.78mm (3.59mm - 1.81mm). However, there was a large increase in the total craniocaudal laxity for the Rottweiler between 160° and 150° (3.14mm and 4.26mm respectively) bringing the total mean increase in craniocaudal laxity between 160° and 110° to 2.66mm. Testing was not done at 160° in the Racing Greyhound.

The effect of fixing the tibia so that it was unable to rotate freely during the craniocaudal tensile loading was to reduce the laxity recorded in the stifle joint in both breeds at all the joint angles tested (table 7.2). In the Rottweiler specimens the mean total craniocaudal displacement was from 2.75mm (SEM 0.58mm) at 160° to 4.27mm (SEM 0.47mm) at 110° and in the Racing Greyhound it was from 1.75mm (SEM 0.26mm) at 150° to 2.91mm (SEM 0.13mm) at 110°. Comparing the mean craniocaudal displacement in the specimens when their tibias were free and fixed at the same joint angles (table 7.2), shows that as the joint was flexed, the percentage increase in the mean craniocaudal displacement resulting from allowing the tibia to rotate freely ranged from 4.7% at 150° to 35.8% at 110° in Rottweilers and 3.4% at

150° to 23.4% at 110° in Racing Greyhounds. In each breed there was a consistent trend of increasing percentage of increase in the craniocaudal displacement with increasing joint flexion (table 7.2).

The individual specimen variations in the values of the total craniocaudal displacement, as indicated by the standard deviations about the mean (table 7.2) show a much greater variation in the Rottweiler compared to the Racing Greyhound specimens.

The results of statistical analysis of the total craniocaudal displacement of the two breeds in the tibia-free specimens (two-sample Student's t-test) are given in table 7.5 and show that the mean values for the Rottweiler are statistically significantly different ($p < 0.05$) from the Racing Greyhound at the same joint angles and also at most different joint angles between the two breeds. The total craniocaudal displacement of the intact stifle joint, where the tibia was free, for the Rottweiler increased statistically significantly (paired t-test - $p < 0.05$) with each increase in joint flexion. The same was found in the Racing Greyhound.

The measured values of the mean maximum cranial displacement at 100N cranial loading are given in table 7.1 and illustrated in fig 7.9. The trends seen are the same as for the total craniocaudal displacement already described. The increase in cranial laxity with increased joint flexion is seen in both breeds but it is greater in the Rottweiler (1.60mm (SEM 0.27mm) at 160° to 2.90mm (SEM 0.35mm) at 110° in Rottweilers and 0.94mm (SEM 0.12mm) at 150° to 1.82mm (SEM 0.13mm) at 110° in Racing Greyhounds). Again, the actual mean increase in the cranial displacement between 150° and 110° was similar in the Rottweiler (0.70mm) and the Racing

Greyhound (0.88mm), with a large increase in the cranial laxity for the Rottweiler between 160^{o} and 150^{o} (1.60mm to 2.20mm). Allowing the tibia to rotate during tensile loading, as with total craniocaudal displacement, resulted in an increase in cranial displacement compared to when the tibia was fixed at the same joint angles (10.0% to 33.0% at 160^{o} - 110^{o} in Rottweilers and 4.4% to 24.6% at 150^{o} - 110^{o} in Racing Greyhounds) (table 7.1). The increase in cranial laxity in the tibia-free joints increased with joint flexion (table 7.1).

The mean values of cranial displacement of the tibia-free to rotate Rottweiler stifle joints were statistically significantly different (two-sample t test $p < 0.05$) from those of the Racing Greyhound at the same joint angles (table 7.6). As in total craniocaudal displacement, the maximum cranial displacement of the intact, tibia-free stifle for the Rottweiler and Racing Greyhound increase statistically significantly ($p < 0.05$) with each increase in joint flexion.

The mean maximum cranial displacement of the CrCL-only Rottweiler and Racing Greyhound stifle joints from series 1 with the tibia both free and fixed are shown in table 7.8. These values cannot be related to those for the intact joint (see series 2 below). The range of the mean maximum cranial displacement of the CrCL-only joints at different joint angles in both breeds was small for both the tibia-free test and the tibia-fixed tests.

These values do not follow the trend of increase or decrease with joint flexion (table 7.8) which was seen with the intact joints. None of the mean maximum cranial displacements of the tibia-free Rottweiler, CrCL-only joints are statistically significantly different from those of the Racing Greyhound at the same stifle joint angles (table 7.7a).

STABILITY OF THE INTACT AND CrCL-ONLY STIFLE JOINTS FROM SERIES 2

The values of the mean maximum cranial displacement of the intact and CrCL-only joints can be directly compared to each other in this series. Table 7.3 shows that the mean maximum cranial displacement at 100N load is greater in the CrCL-only joint compared to the intact joint in both breeds at all the stifle joint angles tested both when the tibia is free to rotate and fixed (except in the Rottweiler at 110° with the tibia fixed). Only at 150° and 160° in the Rottweiler and 150° in the Racing Greyhound are the mean maximum cranial displacements of the intact joint statistically significantly different [a, b, c, d, e, f] ($p < 0.05$) from the mean displacement with the CrCL-only joint. In the Rottweiler, the mean maximum cranial displacement of the intact, tibia-free joint ranged from 1.80mm (SEM 0.23mm) to 3.01mm (SEM 0.52mm) from 160° - 110° joint angle showing increasing displacement with increasing joint flexion, whereas, for the same specimens, the values for the CrCL-only, tibia free joints were 3.01mm (SEM 0.24mm), 3.07mm (SEM 0.18mm), 2.83mm (SEM 0.20mm), 2.80mm (SEM 0.23mm), 3.00mm (SEM 0.21mm) at 160°, 150°, 140°, 130° and 110° respectively. In the Racing Greyhound, the values for the intact, tibia free joint were 0.83mm (SEM 0.14mm) at 150° to 1.67mm (SEM 0.13mm) at 110° showing increasing displacement with increasing joint flexion. In the CrCL-only, tibia free joints the values were 1.83mm (SEM 0.09mm), 1.70mm (SEM 0.15mm), 1.90mm (SEM 0.17mm), 1.80mm (SEM 0.11mm) at 150^{o}, 140^{o}, 130^{o} and 110^{o} respectively. As in series 1 CrCL-only, tibia free joints, there was no trend of increase or decrease in joint stability with increasing joint flexion in the CrCL-only, tibia free joints in series 2. But the mean maximum cranial displacement for the Rottweiler CrCL-only joint in series 2 were statistically significantly different ($p < 0.05$) from the Racing Greyhound at the same joint angles (table 7.7b). There was little difference in the values of the mean maximum cranial displacement of the tibia free, CrCL-only joints (fig 7.11) or in the mean load-displacement curves of these joints at different joint angles (fig 7.8a and b).

There were no statistically significant differences between the mean cranial displacements of the CrCL-only joints at different joint angles in the same breeds. The mean maximum cranial displacements of the joints when the tibia was fixed can also be found in table 7.3. As in the tibia-free tests, the mean maximum cranial displacements of the intact, tibia-fixed joints were statistically significantly different between the two breeds at the same joint angles. The same was true for the CrCL-only joints at 140^{o} and 110^{o} but the mean values were not statistically significantly different at 150^{o} and 130^{o} in the CrCL-only joints.

The percentage contribution of the canine CrCL to the cranial stability of the stifle joints, calculated from the superimposition of the CrCL-only, load-displacement curve over the curve of the same joint when it was intact, are shown in table 7.4. Figure 7.13a illustrates the method of calculating the percentage contribution of the

CrCL to cranial joint stability. From the point on the intact joint load-displacement curve where the cranial loading is 100N (X), a vertical line is drawn to meet the cranial displacement axis (at point Y). From the point on the CrCL-only joint curve which is crossed by line X-Y, a horizontal line to the load axis gives the load (Z) which, when applied to the CrCL-only joint, results in the same cranial displacement as when 100N load is applied to the intact joint (fig 7.13a). The ratio of load Z to 100N load is the contribution of the CrCL to cranial joint stability. Although the sample size is small and there is a wide variation between individual specimens, both breeds showed a decreasing contribution of the CrCL to the cranial stability of the stifle joint at increasing joint angles. In the Rottweiler the percentage contribution decreased from a mean value of 85.3% (SEM 11.3%) at 110^{o} to 21.0% (SEM 2.6%) at 160^{o}, in the Racing Greyhound the decrease was from 98.3% (SEM 1.7%) at 110^{o} to 29.7% (SEM 9.7%) at 150^{o}. There were no statistically significant differences (two sample t-test $p < 0.05$) between the mean percentage contributions of the Rottweiler and Racing Greyhound CrCLs at the same joint angles.

7.5.3 DISCUSSION

The craniocaudal stability testing showed an increase in joint laxity with a decrease in the stifle joint extension angle (ie. an increase in joint flexion) in both the Rottweiler and Racing Greyhound. The mean craniocaudal laxities in the Rottweiler specimens were greater (up to two times) than those of the Racing Greyhound at all the joint angles tested, although the actual increase in laxity of the tibia-free, intact joints were similar in both breeds (Rottweiler 1.54mm, Racing Greyhound 1.78mm). Therefore, although the Rottweiler stifle joint is less stable during craniocaudal loading to +/-100N than the Racing Greyhound, the actual amount of change in that laxity with joint flexion is similar. Because the craniocaudal laxity is greater in the Rottweiler stifle but the change in that laxity from flexion to extension is similar in both breeds, the laxity in the Rottweiler stifle changes relatively less than that of the Racing Greyhound.

At a joint angle of 150°, the craniocaudal laxity of the Racing Greyhound at 100N load (0.94mm (SD 0.40mm)) is similar to that of sheep (1mm - Amis et al 1992). The Rottweiler stifle is more lax at this angle (2.20mm (SD 0.17mm)) and is similar to the craniocaudal laxity seen in man (3mm - Radford 1991). It is suggested that there is greater cranial laxity in the human stifle joint so the joint can fully extend to 180° (Radford 1991). This may help explain why the Rottweiler stifle joint has a greater maximum extension than the Racing Greyhound (chapter 5).

Allowing the tibia to rotate freely during craniocaudal loading of the joint resulted in an increase in craniocaudal laxity at all the angles of the stifle joint tested, up to 35% in Rottweilers and 23% in Racing Greyhounds. This phenomenon was also reported by Fukubayashi et al (1982) who found a 30% increase in craniocaudal displacement in man when the tibia was free to rotate. The rotation, the result of a torque moment due to the helical twist of the ligament fibres (7.1.2.3) may result in some untwisting of the cruciate ligaments on one another and so increase their length and allow greater joint instability and also the collateral ligaments do not become so tight and therefore this also reduces the craniocaudal stabilty.

The trends seen for the total craniocaudal displacement of the intact stifle joint and the cranial displacement only at different joint angles are the same, increasing joint laxity with decreasing joint extension angle (table 7.1 and 7.2). However, it is not always easy to determine the position of zero loading of the intact joint from the inflection point on the load-deformation curves (fig 7.4), especially at greater degrees of joint extension where the curve becomes straighter and more vertical (fig 7.5 and 7.6). Inaccurate placement of the intact joint's zero load position (inflection point) at the centre point between the +100N and -100N load on the graph plotter, will result in either a left or right shift of the load-displacement curve. This will lead to the maximum cranial displacement value being either overestimated or underestimated compared to its true value (fig 7.13b). Therefore less errors occur if the total craniocaudal displacement values are used to describe differences in the data at different joint angles rather than the cranial displacement only measurement, as the former values are independent of the exact positioning of the zero load.

The increase in the cranial displacement of the specimens when all the soft tissues are removed except for the CrCL show that although the CrCL is of primary importance in the cranial stability of the joint, other joint structures provide secondary support to the joint. The contribution of the CrCL to cranial stability appears to increase with joint flexion in both breeds. The results show that either the contribution of the CrCL to craniocaudal stability does increase as the joint flexes, or, as is more likely, the other joint structures including the caudal cruciate ligament, menisci, collateral ligaments joint capsule and osseous geometry contribute more to craniocaudal stability as the joint extends. This latter theory is more likely because the cranial displacement of the CrCL-only joint does not vary much as the joint flexes and extends, whereas the cranial displacement of the same joint decreases as the intact joint extends.

The mean maximum cranial displacements of the CrCL-only stifle joints were not statistically significantly different between the two breeds at different joint angles in the specimens in series 1, whereas they were significantly different at all joint angles in series 2. This shows the importance of exactly repositioning the specimens in the Instron machine to the same placement and orientation as when the joint was intact (series 2), otherwise the results are significantly affected.

The sample size of the series 2 specimens was small (n = 3-4), and although statistical analysis was carried out on the values obtained, they should be interpreted with care.

There have been no comprehensive publications reporting the results of craniocaudal stability testing of the canine stifle joint, the effects of joint angles and any breed variations. Most work on craniocaudal stability has been done in man. Markolf et al (1976) and Radford and Amis (1990) reported greater stability at joint angles of 90^{o} compared to 160^{o}. Kennedy (1974) reported that the CrCL was most taut when the stifle joint was between full extension (180^{o}) and 160^{o} and between 110^{o} and 90^{o} and it was most relaxed between 140^{o} and 130^{o}. However, due to the differences in the modes of locomotion, bipedal versus quadrupedal, and differences in the normal kinematic motion of the stifle joint between man and dogs where in the former, the stifle joint fully extends or even hyperextends but in the latter the stifle joint does not extend to 180^{o}, data on craniocaudal stability and the influence of the CrCL on that stability should not be extrapolated from man to dogs. Because of their quadrupedal gait and the presence of stifle joint flexion throughout the weight-bearing phase of the gait cycle, the canine stifle joint is more CrCL-dependent than the human knee (section 1.4).

7.5.4 CONCLUSIONS

1. The craniocaudal joint laxity increases with a decrease in the stifle joint angle in both the Rottweiler and the Racing Greyhound

2. The Rottweiler stifle joint has greater craniocaudal laxity than the Racing Greyhound at all joint angles between 150^{o} and 110^{o}.

3. The actual increases in laxity between joint angles of 160^{o} and 110^{o} is similar in both breeds.

4. Tibial rotation during craniocaudal loading of the stifle joint increases craniocaudal laxity in both breeds between 160^{o} and 110^{o}.

5. The relative contribution of the CrCL to the cranial stability of the stifle joint decreases as the stifle joint extends.

7.6 TIBIAL PLATEAU ANGULATION

7.6.1 INTRODUCTION

Weight-bearing results in a force being generated in the stifle joint that acts to thrust the tibia cranial relative to the femur. In chapter 2 (2.3.5) a description of the tibial compression test, which simulates weight-bearing and determines the integrity of the CrCL by assessing the ability of the CrCL to counter this force, was given.

This internally generated, active force, which is the result of active muscle forces, compression of the tibial plateau against the femoral condyles and the slope of the tibial plateau, has been named the cranial tibial thrust (Slocum and Devine 1983, Slocum and Slocum 1993). The cranial tibial thrust is antagonised by the stifle flexor muscles (active) and the CrCL and the caudal horn of the medial meniscus (passive) (see sections 1.2.2.1., 1.3 and fig.1.6). Therefore when the CrCL is ruptured the tibia moves cranial relative to the femur during weight-bearing. It has been suggested that one mechanism of CrCL rupture is the presence of a cranial tibial thrust force which exceeds the strength of the CrCL (Slocum and Slocum 1993).

Slocum and Slocum (1993) state that the magnitude of the cranial tibial thrust depends on the amount of femorotibial compression and the slope of the tibial plateau. During weight-bearing, a compressive force is transmitted across the joint at the contact point of the articular surfaces. When the tibial plateau is inclined to the horizontal this force comprises two components. These components are the compressive force acting normal to the tibial plateau and the total, resultant force exercised by the ligaments (primarily the CrCL) and the muscles which is antagonistic to the cranial tibial thrust (fig. 7.14).

In the dog the tibial plateau slopes caudally and distally quite markedly compared to man (1.2.1.2).

A line joining the two centres of stifle and hock joint rotation (which are assumed to be single points for simplicity) is the functional long axis of the tibia.

Slocum and Devine (1983) determined the angle of the tibial plateau relative to the functional long axis of the tibia from lateral radiographs of 16 canine stifle joints and found a mean tibial plateau angle of 22.56 degrees (SD 4.53^{o}) (fig 7.20).

The tibial plateau, however, is not a flat, even surface. It has articular and non-articular areas (1.2.1.2.). The medial articular area is oval-shaped and smaller than the circular lateral articular area, both are convex sagittally and concave transversely (1.2.1.2.). This sagittal convexity can be appreciated radiographically in most cases, and the straight line depicted as the position of the tibial plateau by Slocum and Devine (1983) is in fact the approximate tangent to the curved tibial plateau surface. Also Slocum and Devine's (1983) radiographic determination of the tibial plateau angulation does not allow for any irregularities in the surface or differences between the medial and lateral sides.

As the stifle joint flexes and extends the femorotibial contact point moves caudally and cranially (1.3.2. and Fig. 1.19). Any variation in the angle of the tibial plateau inclination at the femorotibial contact point as the stifle joint flexes and extends will change the magnitude of the cranial tibial thrust force generated during weight-bearing which must be offset, in part, by the CrCL (Slocum and Slocum 1993). A technique to eliminate cranial tibial thrust by levelling the tibial plateau by a wedge osteotomy to work together with more conventional CrCL repairs has been described (Slocum and Devine 1984).

The direct measurement of the angle of the tibial plateau at the femorotibial contact point, both medially and laterally, in canine cadaver specimens is described in this section.

7.6.2 ANGLE OF TIBIAL PLATEAU AT FEMOROTIBIAL CONTACT POINT

7.6.2.1 MEASUREMENT PROTOCOL

The angles of the tibial plateau at the medial and lateral femorotibial contact points were measured in 6 Rottweiler and 7 Racing Greyhound cadaver stifles which had not been used for any previous biomechanical testing. - GROUP 2

The joints were mounted in the stainless steel cylinders as described previously (section 7.4). The Instron 1122 with the rigid lower mounting was used but the upper, 6 degrees of freedom, mounting was changed for a fixed one which could be adjusted to different angles, but once the bolts were tightened would not allow any movement of the mounted specimen except in the direction of the load cell (fig 7.15). The specimen was mounted with the femur in the upper moving crosshead and the tibia in the lower mounting at neutral rotation. Both the upper and lower mountings were set at equal angles to the horizontal, either 65^o, 75^o or 80^o degrees each (fig 7.16), which together resulted in a stifle joint angle of

160^o or 130^o for the Rottweiler specimens

150^o or 130^o for the Racing Greyhound specimens

The tibial plateau contact angle was determined at only one joint angle for each specimen.

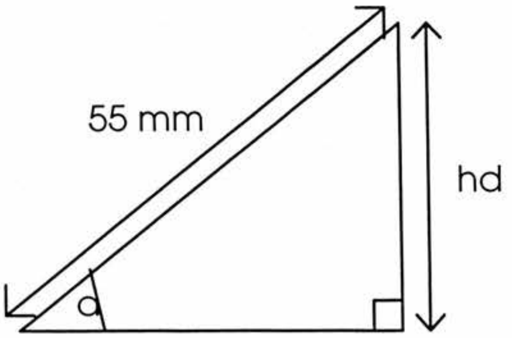
Once the specimens were rigidly mounted, the exact position of the mountings was recorded and the distance between the steel cylinders was measured with calipers. These data allowed the specimens to be remounted accurately for further biomechanical testing at a later stage.

The joint capsule, collateral ligaments, patella, straight patellar ligament and menisci were dissected away, with great care being taken not to disrupt the substance of the cranial and caudal cruciate ligaments or their tibial and femoral attachments. Only the cruciate ligaments were left intact.

A thin (0.25mm), narrow (5mm) piece of rigid metal, 55 mm in length, was carefully inserted between the medial femoral condyle and the medial tibial articular area. The upper crosshead was lowered, bringing the femur towards the tibia until the metal strip was just held between the two bones but there was no visible bending of the metal (fig 7.17). This involved a downward movement of between only 0.3 and 0.8mm in all the specimens tested. The height of the cranial (front) edge of the metal strip above the lower mounting was measured (h_f) and the same for the caudal (back) edge (h_b) (fig 7.18).

$$h_f - h_b = h_d$$

a = angle of the tibial plateau at the femorotibial contact point



$$\sin a = \frac{h_d}{55\,\text{mm}} \qquad a = \arcsin \frac{h_d}{55\,\text{mm}}$$

This procedure was repeated for the lateral side.

In some specimens it was necessary to remove the bony prominence between the proximal tibial tuberosity and the medial and lateral articular areas (fig 1.3 and 1.4) with a rasp as it prevented the metal strip from lying flat at the femorotibial contact point. This procedure did not affect the tibial insertion of the CrCL.

7.6.2.2 RESULTS

Observation of the specimens with the naked eye from the cranial aspect following the removal of the menisci showed that there was a greater distance between the femoral and tibial articular areas on the medial compared to the lateral side in both breeds. There was also more space between the tibia and femur on both sides in the Racing Greyhound compared to the Rottweiler.

Some tibial plateau contact angles sloped downwards from the caudal femur to the cranial tibia (negative angles), others sloped the other way from cranial femur to caudal tibia (positive angles) (fig 7.19).

The degree of tibial plateau angulation at the femorotibial contact point varied between the medial and lateral sides in individual dogs and between the same side in different dogs and different breeds (table 7.9). There was greater variation in the contact angle between the medial and lateral sides in the extended Rottweiler stifle joint, at 160^{o} (mean medial -8.0 $^{\circ}$ and mean lateral -18.0 $^{\circ}$) than the extended Racing Greyhound joint at 150^{o} (mean medial -8.7 $^{\circ}$ and mean lateral +0.3 $^{\circ}$) (table 7.9). At 130^{o} there was greater medial to lateral difference in the Racing Greyhound, mean medial +2.1 $^{\circ}$, mean lateral +16.9 $^{\circ}$ when compared to the Rottweiler at the same joint angles, mean medial +16.5 $^{\circ}$, mean lateral +17.1 $^{\circ}$ although there was greater inter-individual variation in the Rottweiler specimens. When the mid-value between the medial and lateral tibial contact angles is taken for each specimen, the Rottweiler stifle joint slopes at a more negative angle near extension and a more positive angle at 130^{o} than the Racing Greyhound specimens (Rottweiler -13.0 $^{\circ}$ and +16.8 $^{\circ}$ respectively, Racing Greyhound -4.2 $^{\circ}$ and +9.5 $^{\circ}$ respectively).

In the Rottweiler, the values of the tibial plateau contact angles between the medial side at 160^{o} (- 8.0 $^{\circ}$) and 130 ^{0} (+ 16.5 $^{\circ}$) and between the lateral side at 160^{o}

(- 18.0 °) and 130° (+ 17.1 °) were noticeably different. There was also a noticeable difference between the mid-values at 160° (- 13.0 °) and at 130° (+ 16.8 °).

In the Racing Greyhound, there was a greater difference in the values between the lateral side at 150° (+ 0.3 °) and 130° (+ 16.9 °) than between the medial side -8.7 ° (at 150 °) and +2.1 ° (at 130 °).

The mean tibial plateau contact angle of the Rottweiler on the lateral side was more negative than the Racing Greyhound. The mean mid-values of the tibial plateau contact angle of the Rottweiler at extension was noticeably more negative than the Racing Greyhound.

7.6.3 COMPARISON OF RADIOGRAPHICALLY DETERMINED TIBIAL PLATEAU ANGULATIONS AND MEASURED TIBIAL PLATEAU CONTACT ANGLES

An additional series of 6 Racing Greyhound (3 pairs) and 4 Rottweiler (2 pairs) stifles were used to determine the centre of motion of the joints radiographically (Frankel et al 1971, Arnoczky et al 1977), the functional long axis of the tibia (Slocum and Devine 1983) and the inclination of the tibial plateau at the femorotibial contact point relative to the functional long axis of the tibia at different stifle joint angles (section 7.6.2.1).

7.6.3.1 MEASUREMENT PROTOCOL

Each specimen was prepared as described in section 7.2. Two points were marked on the femoral shaft of each specimen, one on the cranial and one on the caudal edge, with 15 millimetre, radio-opaque metal panel pins. The stifle joint was positioned for a lateral radiograph at 150^{o} and the tibia was clamped to prevent any movement. The limb was radiographed at 50kV and 8mA, including from the hock joint to the distal third of the femur. Moving the femur only, the stifle joint was flexed an additional 20 degrees and re-radiographed using the same X-ray plate (double exposure).

From the radiographs the instant centres of rotation (Frankel et al 1971, Arnoczky et al 1977, Panjabi 1979) were determined by the method of Rouleaux which involves drawing a line from between an original point to where it had been displaced during flexion (A to A', B to B'), the intersection of their respective perpendicular bisectors is the position of the instant centre of motion (fig 7.20). To improve the accuracy of the Rouleaux method, the other ends of the pins were also used to give four intersecting lines instead of just two. The inclinations of the tibial plateau to the functional axis of the tibia (Slocum and Devine 1983) were then calculated as shown in fig 7.20.

The stifle joint preparations were then clamped firmly in a series of retort stands at 160^{o} for the Rottweiler and at 150^{o} for the Racing Greyhound stifles. They were not mounted in the stainless steel cylinders or the Instron machine for this series of measurements.

All the peri and intra-articular tissues were removed, leaving only the cruciate ligaments intact as described in section 7.6.2.1. The medial and lateral tibial plateau angulations at the contact points were measured as in section 7.6.2.1 but the femur was lowered manually, by slackening the upper vertical clamp, which did not allow any horizontal or rotatory femoral movement. In this series the tibial plateau angle was measured at a number of joint angles for each specimen:-

Rottweilers	160^{o}, 150^{o}, 140^{o}, 130^{o}, 110^{o}
Racing Greyhounds	150^{o}, 140^{o}, 130^{o}, 110^{o}

7.6.3.2 RESULTS

Fig 7.21 shows the positions of the instant centres of motion of the stifle joints for 4 Rottweilers and 6 Racing Greyhounds as determined from the lateral radiographs. There is some variation between the position of the calculated centres of motion, but they broadly agree with the work of other authors (Arnoczky et al 1977, Ireland et al 1986, Mitton et al 1991).

The inclination of the tibial plateau relative to the functional axis of the tibia, calculated from the lateral radiographs of 4 Rottweiler and 6 Racing Greyhound hind limbs are shown in table 7.10. The mean tibial plateau angle of the Racing Greyhounds was 23.4 degrees (SEM 0.8 ^{o}) and for the Rottweilers it was 22.6 degrees (SEM 2.4 ^{o}). There was no statistically significant difference between the mean values for the Rottweiler and the Racing Greyhound ($p=0.72$).

The mean angles of inclination of the tibial plateau at the femorotibial contact point, medial, lateral and mid-point values for the Rottweiler and Racing Greyhound are given in table 7.11.

As the stifle joint flexes from 160^{o} to 110^{o} the inclination of the tibial plateau at the femorotibial contact point changes from sloping from the caudal femur to the cranial tibia (negative) to slope from the cranial femur to the caudal tibia (positive). This is seen in both breeds but at the extremes of flexion and extension which were measured, the angular change is greater in the Rottweiler compared to the Racing Greyhound, ie. in the Rottweiler from being more negative at 160^{o} (medial - 10.8^{o} (SEM 0.5^{o}) lateral - 18.8^{o} (SEM 0.5^{o}) mid-value - 14.8^{o} (SEM 0.5^{o})) to a more positive angulation at 110^{o} (medial + 21.5^{o} (SEM 1.4^{o}) lateral + 25.0^{o} (SEM 1.1^{o}) mid-value + 23.2^{o} (SEM 0.7^{o})) compared to the Racing Greyhound (medial - 10.4^{o} (SEM 1.1^{o}) lateral - 2.3^{o} (SEM 1.7^{o}) mid-value - 6.3^{o} (SEM 1.0^{o}) at 150^{o} and medial + 11.8^{o} (SEM 1.2^{o}) lateral + 17.0^{o} (SEM 0.4^{o}) mid-value + 14.4^{o} (SEM 0.5^{o})) at 110^{o}) These trends are the same as those reported for the contact point inclinations measured in the Instron machine (section 7.6.2.2).

The mean mid-values of the Rottweiler and Racing Greyhound were statistically significantly different at 140^{o}, 130^{o}, 120^{o} and 110^{o} ($p<0.01$ [a], $p<0.001$ [b], $p<0.001$ [c], $p<0.001$ [d] respectively), but they were not significantly different at 150^{o} ($p=0.14$).

Comparing the medial and lateral angles of inclination in each breed, only at 160^{o} was there a statistically significant difference between the medial and lateral sides in the Rottweiler [e] ($p<0.05$). In the Racing Greyhound there was a significant difference between medial and lateral sides at all the joint angles measured (150^{o} - $p<0.01$ [f], 140^{o} - $p<0.001$ [g], 130^{o} - $p<0.0001$ [h], 120^{o} - $p<0.01$ [i], 110^{o} - $p<0.01$ [j]).

7.6.4 CALCULATION OF THE INCLINATION OF THE TIBIAL PLATEAU

7.6.4.1 METHOD

The lateral radiographs of all the stifle joints (22 Rottweiler and 22 Racing Greyhound) taken prior to biomechanical testing in section 7.2 did not include the hock joint. Also, they were not taken with a view to determining the instant centres of motion as described in section 7.6.3 using radio-opaque markers and double-exposing the radiograph. However, an attempt was made to measure the angle of the tibial plateau relative to the functional axis of the tibia by overlaying these radiographs on ones which included the stifle and hock joints of either a Rottweiler or Racing Greyhound. The dimensions of the hindlimb of individuals of the same breed are similar and by using the hock joint position on one radiograph, the anatomical and functional tibial axes could be drawn on the overlaid radiograph.
In order to standardise the positioning of the instant centre of motion on each radiograph, a series of concentric circles was used and the centre point of the circle which most closely matched the curve of the caudal femoral condyles was taken as the instant centre of motion of that joint (fig 7.22).

From the position of the instant centre of motion, and the anatomical and functional axes, the inclination of the tibial plateau to the functional axes was calculated (fig 7.20, section 7.6.3).

7.6.4.2 RESULTS

The mean (SD and SEM) inclination of the tibial plateau measured from the lateral radiographs taken in section 7.2 for each breed were;

Rottweiler (n = 22) = 19.9 ° (SD 5.9 °, SEM 2.4 °)

Racing Greyhound (n = 22) = 24.6 ° (SD 1.8 °, SEM 0.7 °)

The mean tibial plateau angle of the Racing Greyhound was statistically significantly greater ($p < 0.001$) than the Rottweiler.

The individual values of the calculated inclination of the tibial plateau (radiographically) for those joints whose tibial plateau angulation at the femorotibial contact point were also measured using the Instron machine (section 7.6.2) are given in table 7.9.

The lateral radiographs were taken at between 150° and 140°. Therefore the mean radiographically determined tibial plateau angles are illustrated without reference to the joint angles in table 7.9. The mean calculated tibial plateau angles for the Rottweiler (+19.9 °) is similar to the mean measured mid-value at 130° (+16.8 °) but is noticeably different from that measured at 160° (-13.0 °). For the Racing Greyhound, the mean calculated tibial plateau angle (+24.6 °) is noticeably different from the measured mid-values at both 150° (-4.2 °) and 130° (+9.5 °).

7.6.5 DISCUSSION

The greater distance, observed grossly, between the femur and tibia on the medial compared to the lateral side can be explained by the fact that the medial femoral condyle is smaller than the lateral (1.2.1.1) and the lateral meniscus is thicker than the medial (1.2.2.4).

Slocum and Devine (1983) maintain that the magnitude of the cranial tibial thrust force is determined, in part, by the angle of the tibial plateau to the functional axis of the tibia, and the more variation in that angle, the more variation there will be in the cranial tibial thrust.

Instead of the generalised measurement of the tibial plateau angle from lateral radiographs, this section attempted to measure the tibial plateau angle relative to the femoral condyles at specific points, namely the femorotibial contact points, at different joint angles, and to differentiate between the medial and lateral femorotibial articular areas.

The same trends were seen in the tibial plateau femorotibial contact angles during joint flexion and between the medial and lateral sides in both groups of joints examined (7.6.2 and 7.6.3). In the Rottweiler, the mean tibial plateau contact angles were positive at 130^{o} and similar angles were measured on the medial and lateral sides (table 7.9, 7.11). In the Racing Greyhound at 130^{o}, the lateral slope was similar to the Rottweiler but the medial side was much less positively angled. The almost equal medial-lateral slope in the Rottweiler at 130^{o} will result in a cranial tibial thrust which is antagonistic to the CrCL (fig 7.14). In contrast, in the Racing Greyhound, the greater positive lateral slope will result in a greater cranial tibial thrust on the lateral side and lead to internal tibial rotation so that the cruciate ligaments become tighter as they twist on one another, effectively shortening the CrCL (1.3.1) and resulting in greater craniocaudal stability. The cruciate ligaments are the primary restraint to craniocaudal displacement (1.3.1), therefore it is probable that the greater cranial tibial thrust generated equally, both medial and lateral, in the Rottweiler stifle joint results in a greater strain in the CrCL than the internal tibial rotation caused by the unequal medial and lateral cranial tibial thrust seen in the Racing Greyhound at 130^{o} where the collateral ligaments will help to resist the internal tibial rotation. At greater flexion angles - 110^{o} - there is less difference between the medial and lateral tibial contact angles (table 7.11) and so there will be less tendency for the tibia to internally rotate. Even at 110^{o}, the Rottweiler tibial plateau contact angle is more positive and will result in a greater cranial tibial thrust than the Racing Greyhound (table 7.11).

The mean mid-value of the medial and lateral tibial plateau contact angles in the Rottweiler is greater (either positive or negative) than the Racing Greyhound at 160^{o} and 110^{o} and so the range of change in the magnitude of the average medial and lateral cranial tibial thrust will be greater in the Rottweiler.

The results of the calculation, from the lateral radiographs, of the tibial plateau inclination to the functional and anatomical axis of the tibia (7.6.3 and table 7.10) agree with those of Slocum and Devine (1983) who found a mean tibial plateau inclination of 22.56° (SD 4.53°).

The attempt to determine the tibial plateau inclination to the functional tibial axis (7.6.4) from the lateral radiographs taken in section 7.2 produced mean values which were in good agreement with those in section 7.6.3 and those reported by Slocum and Devine (1983). In the group of cadaver stifles used in section 7.6.4., the mean tibial plateau inclination in the Rottweiler was statistically significantly less ($p<0.001$) than the Racing Greyhound (19.5 ° and 24.6 ° respectively) which was in contrast to the tibial plateau inclinations measured in section 7.6.3 where there was found to be no statistically significant difference between the Rottweiler (22.6 °) and Racing Greyhound (23.4 °) tibial plateau inclinations. However many more measurements of different stifles need to be made before any breed differences could be determined. The tibial plateau angle at the femorotibial contact point cannot be directly related to the tibial plateau inclination because they are measured relative to different axes. The former is measured relative to the horizontal and the latter to the functional tibial axis. The tibial plateau inclination is always angled caudally and distally (positive) whereas the tibial plateau contact angle varies between positive and negative angles during flexion and extension.

It should be remembered at this point that the effects of the menisci and weight-bearing compressive forces on the congruency and angle of contact of the articular surfaces of the stifle joint have been ignored.

7.6.6 CONCLUSIONS

1. The angle of the tibial plateau at the femorotibial contact point usually differs between the medial and lateral sides.

2. The angle of the tibial plateau contact point changes from negative at extension to positive at flexion (at 110^{o}).

3. The range of the tibial plateau contact angle between extension and flexion is greater in the Rottweiler compared to the Racing Greyhound.

4. At 130^{o} there is greater symmetry between the medial and lateral tibial plateau contact angles in the Rottweiler than Racing Greyhound.

5. Asymmetry between the medial and lateral tibial plateau contact angles in the Racing Greyhound may tend towards internal tibial rotation, effective shortening of the CrCL and increased craniocaudal stability.

6. The greater cranial tibial thrust generated equally, medially and laterally, in the Rottweiler stifle probably results in a greater strain in the CrCL than the internal tibial rotational tendancy caused by the unequal medial and lateral tibial plateau contact angles seen in the Racing Greyhound. The collateral ligaments help to resist the internal tibial rotation and therefore they assist the CrCL in maintaining joint stability to a greater extent in the Racing Greyhound than in the Rottweiler.

7.7 MACROSCOPIC CRANIAL CRUCIATE LIGAMENT DIMENSION

To calculate the material properties of the CrCL, the length and cross sectional area of the ligament must be known.

The cranial cruciate ligament lengths and cross sectional areas were measured in the 7 Racing Greyhound and 5 of the 6 Rottweiler stifles of group 2, which had been used in section 7.6.2, plus one extra Racing Greyhound and one different Rottweiler stifle joint.

Racing Greyhound	n = 8
Rottweiler	n = 6

7.7.1 MEASUREMENT OF CRANIAL CRUCIATE LIGAMENT LENGTH

The gross anatomy and geometry of the CrCL is complex. Between its origin and insertion the ligament twists approximately 90 degrees (section 1.2.2.6) and its attachements to the tibia and femur are broad-based and involve a relatively large area. Thus, accurate measurements of the CrCL are difficult and there is no standard method but Haut (1986) reported that the ultimate strain in a ligament decreases as the ligament length increases and so he suggested that it was important to state the ligament length. Dorlot et al (1980) measured the length from the tibial insertion to the middle of the femoral origin. Butler and Stouffer (1983) and Butler et al (1983) took the average of 4 straight measurements from femoral to tibial attachments on the medial, lateral, cranial and caudal borders of the ligament. Vasseur et al (1991) took an average of the length of the craniomedial and caudolateral portions of the ligament. This latter method was adopted in this study.

7.7.1.1 MEASUREMENT PROTOCOL

The length of the cranial cruciate ligaments were measured with calipers to an accuracy of 0.5 millimetres.

The femoral origin of the CrCl lies on the medial surface of the lateral femoral condyle and so it is difficult to position the calipers along the entire length of the ligament as it runs between the femoral condyles.

Therefore, following the measurement of the tibial plateau contact angle, the caudal cruciate ligament was sectioned and the specimen was removed from the Instron machine. The medial femoral condyle was then carefully removed using a junior hacksaw, making sure that no damage was done to the substance of the CrCL or its attachments. The specimen was re-mounted in the Instron machine, in neutral tibial rotation, using the position of the mountings recorded prior to the measurement of the tibial plateau contact angle (section 7.6.2) to exactly re-position the tibia, femur and CrCL relative to each other as they were before the articular tissues were removed.

The length between the femoral origin and the tibial insertion of the craniomedial and caudolateral borders of the CrCL were measured with calipers and the two values were averaged to give the CrCL length.

7.7.1.2 RESULTS

Close inspection of the CrCLs did not reveal any grossly visible, morphologically distinct fibre bundles in the specimens as described by Heffron and Campbell (1978). On flexion and extension, functionally distinct areas, craniomedial and caudolateral (section 1.2.2.6), were clearly visible. In this study the synovium covering the CrCL was not removed prior to loading the specimen to failure (section 7.8) because it was felt that this may have led to some fibre damage on the ligament surface. This may explain why no morphologically distinct bundles were observed in these specimens.

Table 7.12 shows the CrCL lengths of the individual stifle joints and their breed means (SD and SEM). The mean CrCL lengths are very similar in the two breeds (Rottweiler 18.7mm (SEM 0.7mm) and Racing Greyhound 18.2mm (SEM 0.2mm)) and are not statistically significantly different (two sample t-test $p = 0.43$).

7.7.2 MEASUREMENT OF THE CRANIAL CRUCIATE LIGAMENT CROSS SECTIONAL AREA

The cross sectional area of a ligament is difficult to measure because it has an irregular outline. A number of different methods, of varying accuracy, have been used to determine the cross sectional area of stifle joint ligaments. In some, the measuring apparatus comes into contact with the ligament which may result in errors due to distortion of the ligament. These methods include; area micrometer (Walker et al 1964, Noyes and Grood 1976, Noyes et al 1984, Allard et al 1979, Vasseur et al

1985, Woo et al 1990b), mathematical calculations from width and depth measurements with calipers based on the assumption that the ligament has a regular cross sectional shape, elliptic (Bingham and DeHoff 1979, Vassuer et al 1985) circular (Haut and Little 1969) rectangular (Woo et al 1981b, Woo et al 1983, Woo et al 1986, Woo et al 1990b, Woo and Adams 1990), measuring the thickness as a function of the position along the width of the ligament (Shrive et al 1988), gravimetric method measuring the weight and length of a ligament of known specific weight (Matthews and Ellis 1968). The area micrometer squeezes the ligament and has been shown to reduce the cross sectional area recorded by +/- 26% (Race and Amis 1994). Other methods are non-contact but are still poor at recognising concavities of the ligament borders; travelling microscope (Gupta et al 1971), split shadow (Iaconis et al 1987), laser telemetry (Lee and Woo 1988, Woo et al 1990b) and computerised tomography (Reiser et al 1981) which is accurate but complex and expensive. Hubbard and Chun (1988) took paraffin-embedded sections of ligaments and measured the cross sectional areas directly. This was an accurate method but destructive, as the ligaments cannot be biomechanically tested afterwards.

A non-destructive method of measuring the cross sectional area of ligaments and tendons using bone cement duplicates, developed by Race and Amis (1994) has been modified to measure the cross sectional area of the canine CrCL whilst it is still attached to the femur and tibia prior to failure testing.

7.7.2.1 MEASUREMENT PROTOCOL

The specimens used were the same as those in section 7.7.1.

Rottweiler stifles n = 6 Racing Greyhound stifles n = 8

The stainless steel cylinders containing the stifle joint preparations were removed from the Instron machine and mounted in retort stands at the same joint angles and the same distance apart (as measured in section 7.6.2) as they were in the testing machine. The tibia was in neutral rotation relative to the femur. The above procedure ensured that the CrCL was in the same position as when the stifle joint was intact, when the ligament length was measured and as it would be when the preparation was re-positioned in the Instron machine for tensile loading to failure (section 7.8).

A thin 'pseudo-joint capsule' made of plasticine was moulded around the femur-CrCL-tibia complex which bridged the two steel cylinders. A slit was cut at the front of the 'joint capsule' (fig 7.23). Cold-curing silicon rubber[b] and its curing agent were thoroughly and quickly mixed at a ratio of 20 millilitres (ml) silicon rubber to 6 drops of curing agent. Care was taken not to introduce air into the curing silicon rubber during mixing. This was poured through the slit into the pseudo-joint capsule until the latter was full. After 20-30 minutes the plasticine 'joint capsule' was removed (fig 7.24) and the hard silicon rubber mould was cut from the joint specimen with a scalpel blade. A vertical cut was made in the mould down one side which was carefully deepened towards the CrCL. The mould was peeled away from the undamaged CrCL. The result was a silicon rubber block with impressions of the tibial plateau, lateral femoral condyle and a hole representing the CrCL (fig 7.25).

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[b] Ambersil, Bridgewater, Somerset, England. Silcoset 105

The silicon mould was used to duplicate the CrCL using polymethylmethacrylate[c] (bone cement). The ratio of the liquid and powder parts of the bone cement were carefully measured. 20ml liquid : 23 g powder. After 30 minutes the mould was cut away leaving the solid bone cement duplicate of the CrCL, tibial plateau and lateral femoral condyle (Fig 7.26).

The cross sectional area of individual CrCLs was measured at three different positions along the ligament length.

A = most proximal part of the CrCL just distal to its femoral origin

B = mid-point between the femoral and tibial attachments

C = most distal part of the CrCL before its tibial insertion

Sections of the bone cement CrCL, one millimetre thick, were cut perpendicular to the axis of loading of the ligament (see section 7.8) at the specified positions along the CrCL length using a 0.25 millimetre thick, high speed, steel circular saw. The sections were photographed under a binocular microscope with a scale ruler in the field of view (Fig 7.27). The area (mm^2) of each photographed section was measured using a Videoplan digitising, image analysis program on a computer.

[c] CMW3 original bone cement, CMW laboratories, Dentsply Blackpool, England

7.7.2.2 CORRECTION FOR ERRORS DURING THE MEASUREMENT OF THE CRANIAL CRUCIATE LIGAMENT CROSS SECTIONAL AREAS

Possible sources of error during the measurement of the cross sectional area using the above method include;

1, silicon rubber expansion or contraction

2, bone cement expansion or contraction

3, error in calibrating the videoplan digital analyser from the scale ruler on the photograph

4, not cutting a correct transverse plane

A solid stainless steel cylinder (control) with a diameter of exactly 10mm was subjected to exactly the same procedures as the CrCL to produce a bone cement duplicate (Fig 7.28). Six sections were cut perpendicular to its long axis and the photographic and area-measuring procedures were also repeated

The area (a) of a circle of known diameter can be calculated mathematically.

$$a = \pi \times r^2 \quad \text{(r = circle radius)}$$

If the measured area does not equal the theoretical, calculated area, a correction factor can be applied to all the measured CrCL areas.

7.7.2.3 RESULTS

Correction for error in cross sectional area measurement

For the 10mm diameter steel cylinder control:

Calculated cross sectional area $a = \pi \times (5)^2$

$= 78.54\ \text{mm}^2$

Mean measured cross sectional area of 6 control sections

$= 75.09\ \text{mm}^2$ (SEM $0.50\ \text{mm}^2$)

The measured cross sectional area was smaller than the calculated value. Therefore to correct the measured values of the CrCL cross sectional areas for error, the measured values must be multiplied by a factor of

$$\frac{78.54\ \text{mm}^2}{75.09\ \text{mm}^2} = 1.05$$

The mean measured cross sectional areas (corrected) of 6 Rottweiler and 8 Racing Greyhound CrCLs at three positions along their length are given in table 7.13. In both breeds, the mean mid-ligament cross sectional area is less than the areas near the boney attachments of the CrCLs. At all three measured positions the Rottweiler CrCL had a greater mean cross sectional area than the Racing Greyhound (table 7.13) (Rottweiler 28.18mm^2 (SEM 2.93mm^2)-proximal, 26.40mm^2 (SEM 2.96mm^2)-mid-ligament, 31.17mm^2 (SEM 3.03mm^2)-distal, Racing Greyhound 21.43mm^2 (SEM 1.39mm^2), 20.41mm^2 (SEM 1.31mm^2), 21.46mm^2 (SEM 0.96mm^2)

respectively). Because the variation of individual specimens about the mean, as illustrated by the standard deviations, were quite large, especially in the Rottweilers, the mean mid-ligament cross sectional area of the Rottweiler CrCLs was not statistically significantly different (two-sample student's t test) from the Racing Greyhound despite the large difference in their mean values (Rottweiler 26.40mm^2 (SEM 2.96mm^2) Racing Greyhound 20.41mm^2 (SEM 1.31mm^2)).

If the measured cross sectional areas are divided by the body weight of the cadaver, ie. normalising the cross sectional area to body weight, there is little difference between the two breeds (table 7.14) with normalised mean mid-ligament cross sectional areas of, in the Rottweiler 0.68mm^2/kg body weight (SEM 0.08mm^2/kg) and in the Racing Greyhound 0.65mm^2/kg body weight (SEM 0.03mm^2/kg) and they were not statistically sigificantly different.

The mean values of the proximal and distal portions of each breed were statistically significantly different, both before and after correction for body weight.

7.7.3 DISCUSSION

The mean CrCL lengths of the Rottweilers and Racing Greyhounds are similar although the Rottweiler exhibited greater individual variation within the breed. The mean values are similar to those reported by other authors for dogs of similar body size (Butler and Stouffer 1983 - 15.3mm, Butler et al 1983 - 17.8mm, Vasseur et al 1985 - 18.6mm, Vasseur et al 1991 - 20.5mm).

The cross sectional areas, measured using the non-destructive method described, showed an increase near the bony attachments of the CrCL where the ligament fans out to attach to the tibia or femur. The large attachment areas allow the loads transmitted by the ligament across the joint to be spread over a greater area and so reduce the load concentration per unit area of the ligament-bone transitional zone. Although the mid-ligament cross sectional areas of the two breeds were not statistically significantly different, the Racing Greyhound CrCLs were noticeably thinner than the Rottweiler CrCLs. This difference, however disappeared when the cross sectional areas were corrected for the differences in body weight.

The mean values of the canine CrCLs given here are greater than those reported by other authors but this method has not been used previously for the determination of the cross sectional areas of canine CrCLs so there can be no direct comparison with other studies. (Butler et al 1983 - 11.5mm^2, Vasseur et al 1985 - 16.6mm^2 and 14.9mm^2, Vasseur et al 1991 - 18.54mm^2).

The dimensions of the CrCLs of the two breeds are informative in themselves but the main purpose of their measurement is to use in section 7.8 to determine the material properties of the CrCL substance.

7.8 STRUCTURAL AND MATERIAL PROPERTIES OF THE CANINE CRANIAL CRUCIATE LIGAMENT

The structural (mechanical) properties of the femur-CrCL-tibia complex and the material properties of the CrCL were determined by tensile loading the preparations in the Instron 1122 materials testing machine at a high strain rate. The load-deformation curves were recorded from zero loading to complete macroscopic failure of the ligament by the integral graph plotter described in section 7.5.

7.8.1 TEST PROTOCOL

All the Rottweiler and Racing Greyhound stifle joint preparations subjected to craniocaudal stability testing or measurement of the CrCL length, cross sectional area and the tibial plateau angles at the femorotibial contact point (7.6.2) were tested to ultimate failure by tensile loading. Only the 4 Rottweiler and 6 Racing Greyhound stifle joints used in section 7.6.3 were not tested to failure.

Two different axes of tensile loading were tested and recorded but the loading rate and recording of the load-deformation curves were the same for each.

In this study the measured displacement of the tibia from the femur is taken to be the same as the change in length of the CrCL during tensile loading although Woo et al (1981b) suggest that the non-uniform geometry and strength of the ligament means that this assumption is not strictly correct.

The integral graph plotter was re-calibrated for a full scale deflection (paper width) representing 5KN load. Once the specimens were mounted in the Instron machine (details and the differences in the mountings are described in sections 7.5 and 7.6.2) the load control was set with the pen at the extreme left of the scale and the upper crosshead was programmed to move vertically upwards at a rate of 1000mm/min (16.67mm/s) until it was stopped manually after complete macroscopic ligament failure. The paper speed was set at a ratio of 1:1 so that 10mm on the recording paper represented an actual crosshead displacement, and so CrCL elongation, of 10mm.

crosshead speed = 1000mm/min = 16.67mm/s

$$\text{mean strain rate for Rottweiler stifles} = \frac{16.7\text{mm / s}}{18.7\text{mm}} = 89.3\%$$

(crosshead speed ÷ mean initial ligament length)

$$\text{mean strain rate for Racing Greyhound stifles} = \frac{16.7\text{mm / s}}{18.2\text{mm}} = 91.7\%$$

(crosshead speed ÷ mean initial ligament length)

These strain rates are similar to those used by other authors (Alm et al 1974, Bulter and Stouffer 1983, Butler et al 1983, Vasseur et al 1985, Vasseur et al 1991) and were chosen to mimic the physiological loading rate experienced by the stifle joint during CrCL injury in vivo (Noyes et al 1974a, Amis 1985).

7.8.2 CRANIAL LOADING TO ULTIMATE FAILURE AT DIFFERENT JOINT ANGLES

All the specimens which were tested for craniocaudal stability when intact and when only the CrCL remained (section 7.5) were tested to ultimate failure at one of two joint angles. Two additional Rottweiler CrCLs were tested, one at 160^{o} and one at 130^{o}. One extra Racing Greyhound CrCL was tested at 150^{o}. All 3 specimens were previously unused.

Rottweiler joints tested at	160^{o} joint angle	n = 8
	130^{o} joint angle	n = 6
Racing Greyhound stifles at	150^{o} joint angle	n = 7
	130^{o} joint angle	n = 6

The Instron mountings were unchanged from the craniocaudal stability testing (section 7.5) where the tibia was mounted horizontally and able to rotate freely in the moving upper crosshead and the femur was rigidly fixed to the base of the machine. Once the stifle joint had been positioned at the correct joint angle, the CrCL was loaded by the upward movement of the upper crosshead. This resulted in a tension force acting on the joint (fig 7.29).

The graph plotter recorded the tensile load as a function of the deformation of the bone-ligament-bone complex (displacement of the upper crosshead from the position of zero loading). The upward movement of the tibia was halted manually when the

CrCL had ruptured macroscopically (fig 7.30), although the dramatic fall of the load-deformation curve may occur whilst the ligament looks grossly intact (Kennedy et al 1976). The mode of failure of individual specimens was recorded but no histology was carried out on the ruptured specimens. 3 modes of failure are generally recognised (Noyes et al 1974a);

1) Ligament failure - ruptured collagen bundles throughout the ligament (mid-substance).

2) Avulsion - mainly through cancellous bone immediately below dense cortical bone.

3) Ligament-bone cleavage - through all 4 zones of attachment (see section 1.2.2.6).

7.8.3 LOADING TO ULTIMATE FAILURE ALONG THE LIGAMENT AXIS (STRAIGHT LOADING)

The specimens tested to ultimate failure here were those used in sections 7.6.2 and 7.7. (CrCL length, cross sectional area and tibial plateau contact angle). The stifle joint specimens were tested at one of two joint angles.

Rottweilers tested at	160^{o} joint angle	n = 3
	130^{o} joint angle	n = 3
Racing Greyhounds tested at	150^{o} joint angle	n = 4
	130^{o} joint angle	n = 4

The mounting fixtures of the Instron machine used in this test were the same as those described for the measurement of the tibial plateau femorotibial contact angle (section 7.6.2, fig 7.15 and 7.16). Both the femur and tibia were rigidly fixed in neutral rotation with the femur in the upper mounting, unlike in section 7.5. By symmetrically adjusting the angles to the horizontal of the upper and lower mountings, the required joint angles (160^{o}, 150^{o}, 130^{o} degrees) were obtained with the loading axis as close to the long axis of the CrCL as possible (fig 7.16 and 7.31) (straight loading).

Upward motion of the crosshead tensile loaded the CrCL along its axis until complete failure was achieved.

The graph plotter recorded the load-deformation curve of each specimen. As in section 7.8.2 the mode of failure was recorded but histology was not done.

A schematic diagram of an average, normal load-deformation curve from zero loading to ultimate failure is illustrated in fig 7.32. The initial shallow slope on the load-deformation curve is where the crimped ligament fibres (section 1.2.2.6) straighten so there is a relatively large deformation with little increase in joint loading. The linear portion is the elastic phase and the last portion of the slope before the rapid fall in load is the plastic phase where the stretching of the ligament has become irreversible.

STRUCTURAL (MECHANICAL) PROPERTIES which correspond to the tensile properties of the bone-ligament-bone complex as a whole can be measured directly from the load-deformation curve. They include ultimate load (N), ultimate deformation (mm), linear stiffness (N/mm), energy absorbed at failure (J). Definitions of these properties are given in the glossary and they are illustrated in figure 7.32. The greater the stiffness of the specimen, the greater the load that is required to deform it by a unit length. The energy at failure is the energy needed to fail the specimen and is the area under the load-deformation curve to the point of failure and in this study it was measured using the same video image analyser described in section 7.7.2 to determine the ligament cross sectional area.

MATERIAL PROPERTIES reflect the tensile properties of the CrCL substance only and they are independent of the ligament length and the properties of the ligament boney attachments. Noyes et al (1974a) described the material properties as normalisations of the structural properties. These properties are represented on a stress/strain curve (fig 7.33) which can be calculated from the load-deformation curves and the CrCL dimensions determined in section 7.7.

The material properties calculated in this study include;

Mean strain (percent %) which reflects the change in the specimen dimensions under loading related to the initial specimen dimensions. Only the mean strain can be calculated in view of the range of fibre lengths within each ligament. Calculating the ligament strain helps minimise the influence of errors in the measurement of the ligament length.

Stress (MPa) which relates the load in the ligament to the cross sectional area of the ligament. In this study the stress values are 'nominal' (engineering) rather than 'true' because the stresses were calculated, based on the original ligament cross sectional areas and not on the reduced cross sectional area accompanying tensile loading (McGraw Hill 1991).

Tensile strength (MPa) This is the maximum stress which a specimen can withstand and relates ultimate loads to specimen cross sectional area.

Ultimate strain (percent %) This is the amount of stretching which a ligament can withstand before it fails relative to its original length.

Tangent Modulus of elasticity (MPa) This expresses the inherent stiffness of the ligament substance regardless of its length and it is a constant, relating unidirectional stress and strain (New Encylopaedia Britannica 1992). It is the slope of the line which is tangent to the stress/strain curve within a specified range of strains. In this study, the ligament strain and therefore tangent modulus, was calculated over the range of 3-7mm deformation from the load-deformation curve of each specimen.

Definitions of these properties are given in the glossary and they are illustrated in figure 7.33.

7.8.4 RESULTS

Of the stifle joint specimens cranially loaded to ultimate failure, 1 Rottweiler and 2 Racing Greyhound specimens tested at 160^{o} and 150^{o} respectively suffered premature fractures at the distal femoral epiphysis on loading and being unable to remount them satisfactorily, the specimens were discarded from the study.

Early in the biomechanical testing one other Rottweiler specimen fractured through the femoral shaft when loaded. It was re-mounted and tested to failure. Subsequently the specimens were more deeply embedded in the bone cement to reduce the bending moments acting on the tibial and femoral shafts.

CRANIAL LOADING

The mean structural and material properties of the Rottweiler and Racing Greyhound CrCL at the 2 joint angles are shown in tables 7.15 and 7.16. Because the CrCL lengths and cross sectional areas of these specimens were not determined, the mean values of those measured in section 7.7 were used to calculate the material properties in table 7.16.

The individual ultimate loads for the two breeds at the different joint angles are shown in fig 7.34, and the mean ultimate loads for each breed are illustrated in fig 7.35. The mean ultimate loads of the Rottweiler femur-CrCL-tibia complex were 2130N (SEM 378N) at 130^{o} and 1389N (SEM 137N) at 160^{o}. There was no statistically significant difference between the two joint angles. The mean ultimate loads of the Racing Greyhound specimens tested at 130^{o} and 150^{o} were 1799N (SEM 145N) and 1897N (SEM 156N) respectively. Again there was no statistically significant difference. Comparing the mean ultimate loads of the two breeds at the same (130^{o}) or similar (160^{o} and 150^{o}) joint angles, there was no statistically (two-sample t test) significant difference between the breeds at 130^{o}, but at 160^{o} (Rottweiler 1389N) and 150^{o} (Racing Greyhound 1897N) the ultimate loads were statistically significantly different [a] ($p<0.05$). When the ultimate loads were normalisd for body weight (table 7.15), the mean ultimate load/kg body weight in the Rottweiler specimens at 160º and at 130º were not statistically significantly different. The mean ultimate load/kg body weight of the Rottweiler specimens at 160º and the Racing Greyhound at 150º were statistically significantly different [b] ($p < 0.001$), as were the differences between the Rottweiler at 160º and the Racing Greyhound at 130º [c] ($p<0.001$). There was little variation and no statistically significant differences between the mean ultimate deformation (mm) at the two joint angles tested in either breed or between the breeds at the same joint angles (table 7.15)

The mean linear stiffness of the femur-CrCL-tibia complex (table 7.15) was greater in the Racing Greyhound at 150º than in the Rottweiler at 160º and they were statistically significantly different [d] ($p < 0.05$). Although the mean linear stiffness values were greater in the Rottweiler than the Racing Greyhound at 130º, they were not statistically significantly different. The mean linear stiffness was greater at 130º than 160º in the Rottweiler whereas the reverse was true for the Racing Greyhound but neither were statistically significantly different.

The mean energy absorbed at failure (J) was similar for the two breeds at the same angles and for the same breeds at different angles (table 7.15). Only the Racing Greyhound at 150º was noticeably lower (8.8J (SEM 0.8J)) but it was not statistically significantly different.

The mean tensile strength (table 7.16, fig 7.36) of the CrCL was greater at 130º (80.7MPa (SEM 14.3MPa)) than at 160º (52.6MPa (SEM 5.2MPa)) in the Rottweiler but they were not statistically significantly different. There was little difference between the different joint angles in the Racing Greyhound (93.0MPa (SEM 7.6MPa) at 150^{o} and 88.2MPa (SEM 7.1MPa) at 130^{o}) and they were not statistically significantly different. The mean tensile strength of the Rottweiler CrCL at 160^{o} was statistically significantly lower than the Racing Greyhound at 150^{o} [a] ($p < 0.01$) and the mean tensile strength of the Rottweiler at 160^{o} was statistically significantly lower [b] than the Racing Greyhound at 130^{o}. When the mean tensile strengths are normalised to cadaver body weight, the Racing Greyhound value at 150^{o} is statistically significantly greater than the Rottweiler at 160^{o} [c] ($p<0.001$) and at

130^{o} ($p<0.05$). The value for the Racing Greyhound at 130^{o} is significantly different from the Rottweiler at 160^{o} [d, e] ($p<0.001$) and at 130^{o} ($p < 0.05$).

Part of the cranial motion is swinging of the CrCL rather than the extension of it. Therefore 'strain' (displacement divided by original ligament length) is not the correct term for the cranial tibial displacement tests. The term ultimate elongation ratio will be used instead of ultimate strain. The latter is still used for the straight ligament loading tests where the swing motion is not seen.

The ultimate elongation ratio at ligament failure was greater in the Rottweiler CrCL than the Racing Greyhound at both joint angles (table 7.16). There were no statistically significant differences between the ultimate elongation ratios of the two breeds.

The mean tangent modulus (table 7.16) was statistically significantly [f] ($p<0.001$) greater in the Racing Greyhound at 150^{o} than the Rottweiler at 160^{o}. The mean tangent modulus was statistically significantly greater at 150^{o} than at 130^{o} in the Racing Greyhound [g] ($p< 0.05$). The inverse was true in the Rottweiler where the tangent modulus was greater at 130^{o} than at 160^{o} but this was not significant.

There were not enough specimens to draw any conclusions about the modes of failure of the CrCLs in different breeds at the different joint angles (table 7.15). The number of avulsion fractures seen when the CrCL is loaded to failure (cranially or straight loaded - tables 7.15 and 7.17) may seem to indicate that the methods of loading are grossly unphysiological because avulsions of the ligament (usually from the tibia) are rarely seen in the natural disease. However, although large bone/cartilage avulsed fragments are not commonly seen small avulsion fractures occur where a small fragment of bone/cartilage is attached to the substance of the avulsed CrCL. In tables 7.15 and 7.17 the avulsion mode of failure includes these ruptured CrCLs with a small fragment attached.

LOADING ALONG THE LIGAMENT AXIS (STRAIGHT LOADING)

The structural and material properties of the Rottweiler and Racing Greyhound CrCLs, when they are loaded along the ligament axis, are shown in tables 7.17 and 7.18.

There were few statistically significant differences between the mean values of the structural and material properties described in this section. Only the values of the tensile strength, normalised to body weight, and the ultimate strain showed any statistically significant differences.

The mean ultimate loads were similar in both breeds at both joint angles (Rottweiler 1643N (SEM 286N) and 1738N (SEM 476N) at 160° and 130° respectively, Racing Greyhounds 1421N (SEM 150N) and 1781N (SEM 138N) at 150° and 130° respectively.

There was little difference between the mean ultimate deformations in each breed or at the different joint angles.

The mean linear stiffness was greater in the Rottweiler than the Racing Greyhound at both joint angles but there was no difference between the different joint angles in the same breeds.

Again, the mean energy absorbed at failure was similar in both breeds at both angles except the Racing Greyhound at 150° (4.1J (SEM 0.8J).

The mean tensile strength and the tensile strength normalised for body weight were greater in the Racing Greyhound at both joint angles (table 7.18). The mean tensile strength, normalised for body weight, of the Rottweiler CrCl at 160° was statistically significantly lower [a] than the Racing Greyhound at 130°.

There was little difference between the mean ultimate strain in each breed or at the different joint angles. Rottweiler 38.1% (SEM 6.3%) and 35.1% (SEM 1.7%) at 160° and 130° respectively, Racing Greyhound 37.7% (SEM 3.3%) and 44.2% (SEM 1.1%)) at 150° and 130° respectively. The mean ultimate strain of the

Rottweiler at 130^{o} (35.1%) was statistically significantly lower [b] ($p < 0.05$) than the Racing Greyhound at 130^{o} (44.2%).

The mean tangent modulus (table 7.18) was similar at different joint angles in the same breed.

7.8.5 DISCUSSION

The effects of tensile loading Rottweiler and Racing Greyhound femur-CrCL-tibial complexes to failure along two different axes were examined in this section.
The loading directions were along the ligament axis (7.8.3) and loading the tibia cranially as for a cranial drawer stability test only there was no maximum tensile load at which the loading direction would have been automatically reversed (fig 7.29 and 7.31).
Comparing the results of the two loading axes showed that there were a number of individual variations within the breeds which resulted in large deviations from the mean. The mean values for the measured and calculated structural and material properties differed between the two loading axes (table 7.15-7.18). For the tensile loading tests, different setups in the Instron 1122 machine were used for each loading axis (7.5 and 7.6.2). For cranial-tibial loading, the tibia was set in the mounting which allowed 4 degrees of freedom including free tibial rotation. For the ligament axis loading the only movement possible was the vertically upward movement of the upper femoral crosshead.
The effect of free tibial rotation on the craniocaudal stability of the stifle joint was discussed in section 7.5 and Kennedy et al (1980) showed that greater forces were needed to produce smaller deformations when the tibia was fixed and unable to rotate. Thus the femur-CrCL-tibia complex exhibited a greater stiffness when the tibia was fixed. In view of the above, although comparisons will be made here between the two different loading axes, any differences may be, to an unknown degree, due to the mounting apparatus used.

Comparing the tensile properties of the two breeds at different joint angles while cranial-tibial loading to failure showed similar mean ultimate deformations in both breeds which were unaffected by the joint angle. The mean energy at failure, mean ultimate load and mean tensile strength of the Rottweiler specimens increased with increasing joint flexion, the latter two properties being lower at 160^{o} but nearly equalling the tensile strength and increasing above the ultimate load of the Racing Greyhound at 130^{o}. These properties in the Racing Greyhound were virtually unaffected by the joint angle, the ultimate load even decreasing slightly with increased flexion. The mean linear stiffness and mean tangent modulus of the Rottweiler increased with increased flexion whereas the reverse was true of the Racing Greyhound. Mean ultimate elongation ratio was greater in the Rottweiler than the Racing Greyhound, therefore the Rottweiler CrCL elongated more than the Racing Greyhound relative to their original length at both joint angles tested. Neither breed was affected by the change in joint angle.

Tensile strength is ultimate load divided by cross sectional area and cross sectional area is a constant in this study because only the initial cross sectional area prior to loading was measured, therefore if the ultimate load is affected by the joint angle, the tensile strength can be expected to be affected too. Because the ultimate deformation is similar at both joint angles tested and the ultimate load increases with increased flexion, the energy at failure, the area under the load-deformation curve will increase accordingly with joint flexion. Linear stiffness is the slope of the load-deformation curve and because the ultimate deformation was unaffected but the ultimate load increased with increased joint flexion, the angle of the slope of the curve (linear stiffness) should increase, which it did. The amount of decrease in the linear stiffness with increased flexion in the Racing Greyhound was more unexpected. Due to the small decrease in ultimate load with joint flexion, a small decrease in linear stiffness would be expected. The tangent modulus will be affected similarly to the linear stiffness.

Previously published studies have tensile loaded bone-ligament-bone complexes along the tibial axis and therefore too much emphasis on a direct comparison to the presented results for cranial-tibial loading would be inappropriate. However, the results of tibial axis loading of canine CrCLs are similar to those detailed above in order of magnitude.

	ultimate load (N)	**ultimate deformation (mm)**	**linear stiffness (N/mm)**	**energy at failure (J)**	**tensile strength (MPa)**	**tangent modulus (MPa)**
Alm et al 1974	665	5.4	124.1	-	-	-
Butler et al 1983	1068	6.4	348.1	4.3	144	543.8
Figgie et al 1986	1181	7.9	-	9.8	-	-
Vasseur et al 1991	1531	9.4	180.6	6.99	82.6	226.7
Wingfield 1994						
Rottweiler						
160^o	**1389**	**15.86**	**148.0**	**11.5**	**52.6**	**94.1**
130^o	**2130**	**14.83**	**194.8**	**12.8**	**80.7**	**139.7**
R. Greyhound						
150^o	**1897**	**11.40**	**224.6**	**8.8**	**93.0**	**201.8**
130^o	**1799**	**13.83**	**158.3**	**11.5**	**88.2**	**130.3**

The similarity between the effects of joint flexion reported by other authors and the work presented here varies. Figgie (1986) reported a decrease in ultimate load with increased joint flexion (also Woo et al 1987a - rabbit), this was also observed here with the Racing Greyhound specimens when cranial-tibial loaded but the opposite was found in the Rottweilers. The same trend was seen with the linear stiffness where Figgie (1986) reported a decrease with increased flexion, as was seen in the Racing Greyhound but again the opposite in the Rottweiler.
Comparing the results of the ligament axis loading to cranial-tibial loading, the mean ultimate deformation at cranial-tibial loading was approximately twice the value when the ligament axis was loaded. This is probably due mainly to the fact that part of the cranial-tibial motion is swinging of the CrCL rather than the extension of it. However, the cranial tibial loading may also provide a greater shearing component to the tensile load than the ligament axis loading, resulting in greater slipping of the collagen fibres relative to one another and a more gradual mircoscopic disturbance to the ligament integrity.

The energy absorbed at failure with cranial loading (area under the load-deformation curve) was also approximately twice that for the ligament axis loading and results from the greater ultimate deformation.

Linear stiffness and tangent modulus are up to a third lower in the cranial-tibial loaded specimens, again the result of the high ultimate deformation of the ligament. The high deformation means that for every unit of load, the ligament elongates significantly and therefore results in a low linear stiffness, high strain and so a low tangent modulus. Also the tibia was unable to rotate freely during the ligament axis loading and the femur-CrCL-tibia complex will exhibit greater ligament stiffness than when the tibia is free to rotate (Kennedy et al 1980).

7.8.6 CONCLUSIONS

1. The tensile strength of the Racing Greyhound CrCL was greater than the Rottweiler CrCL when the ligament was cranial-tibial tensile loaded to failure in extension.

2. The tensile strength of the Rottweiler CrCL increased with increased joint flexion to 130^{o} when it was cranial-tibial tensile loaded to failure.

3. During cranial-tibial tensile loading the Rottweiler CrCL elongated more, relative to its original length, than the Racing Greyhound CrCL.

4. Cranial-tibial tensile loading at decreasing stifle joint angles increased the linear stiffness of the femur-ligament-tibia complex in Rottweilers but decreased it in Racing Greyhounds.

5. Cranial-tibial tensile loading at decreasing stifle joint angles increased the tangent modulus of the CrCL in Rottweilers but decreased it in Racing Greyhounds.

6. The linear stiffness of the femur-ligament-tibia complex was greater in the Rottweiler than the Racing Greyhound during tensile loading to failure along the CrCL axis.

7. The energy absorbed by the femur-ligament-tibia complex at failure was greater when it was cranial-tibial loaded compared to when it was tested to failure along the CrCL axis.

7.9 SUMMARY

In the introduction to this chapter, a number of different variables which have been reported at various times to influence the biomechanical properties of ligaments were described.

In the subsequent biomechanical testing, the number of specimen and experimental variables were reduced to the minimum to standardise the tests as much as possible. The author had no control over the age, body weight or previous history of the specimens, although radiography of each specimen was carried out to eliminate diseased stifle joints. Carefully controlled specimen preparation and test protocols minimised specimen dehydration and storage deterioration.

All the specimens in each test were treated identically. During craniocaudal stability testing, all the tests were carried out at the same deformation rate, to the same maximum load, loaded along the same axis with pre-conditioning cycles followed by the recording of 4 consecutive gait cycles. The only deliberate variables were the joint angles and the free or fixed tibia.

During loading to failure, the only variables were the loading axes and the joint angles.

Throughout all the tests of craniocaudal stability, loading to failure and measurement of the CrCL dimensions, the Rottweiler specimens exhibited greater individual variation than the Racing Greyhounds.

Injury to the CrCL is the result of a combination of complex factors resulting in forces of different magnitudes acting on the CrCL in a number of different directions. In the biomechanical testing described above, the stifle joint was unidirectionally loaded which is not strictly physiological and so care is needed if this data is being extrapolated to clinical CrCL injury.

Stifle joint craniocaudal stability of both breeds decreased with decreasing joint extension angle, the Racing Greyhound stifle joint being more stable (similar to sheep) than the Rottweiler (similar to man). The greater Racing Greyhound joint stability may be due to a tighter CrCL allowing less craniocaudal displacement. This theory is supported by the fact that cranial displacement of the joint was still greater in the Rottweiler compared to the Racing Greyhound when all the soft tissues including the menisci were removed and only the CrCL resisted the craniocaudal displacement (table 7.3 and 7.8). However, the fact that the percentage contribution of the CrCL to craniocaudal stability was approximately the same in both breeds (table 7.4) and the ultimate elongations when the CrCLs were loaded to failure were again similar in both breeds (table 7.15 and 7.18) tend to dispute this theory. The greater Racing Greyhound stability may be due solely to the other soft tissue structures and osseous geometry of the stifle joint.

The strain in the Rottweiler femur-ligament-tibia complex was greater than the Racing Greyhound during cranial-tibial tensile loading which implies that the Rottweiler specimen was elongated, 'stretched', more at a lower load than the Racing Greyhound which would lead to greater craniocaudal laxity but this would only be

relevant at high loads. As described above (7.8.5.), the greater apparent elongation of the CrCL when the joint was cranially loaded compared to loading along the ligament axis may be partly explained by the swing of the CrCL rather than the extension of it during cranial loading.
However, Woo et al (1983) stated that the true elongation of the ligament substance alone was less than that measured by recording the displacement of the femur-ligament-tibia complex during tensile loading and this implied that the ligament stretch was non-uniform with a high deformation at the ligament-bone junctions. This idea could explain some of the differences between the recorded data for the 2 loading axes tested. The differences could be true differences in the tensile behaviour of the CrCL at different loading axes, or a higher ligament-bone deformation during craniocaudal loading resulting in a greater deformation being recorded than actually occured within the ligament substance and lead to higher ultimate deformations and ultimate strains and lower linear stiffness, energy at failure and tangent modulus being recorded and calculated.

The tibial plateau femorotibial contact angles could have a profound effect on the magnitude of the load acting on the CrCL at different joint angles because the cranial tibial thrust acting antagonistically to the CrCL is dependent on the tibial plateau angle. The tibial plateau femorotibial contact angle varied much more in the Rottweiler than the Racing Greyhound and from 140^{o} - 110^{o}, the tibial plateau contact angle was directed in such a way (positive) as to result in a large cranial tibial thrust to load the CrCL greater than the Racing Greyhound. Slocum and Devine

(1983) suggested that one mechanism of CrCL rupture is the presence of a cranial tibial thrust force which exceeds the strength of the CrCL.

Therefore the Racing Greyhound specimens tested had greater CrCL tensile strength, greater CrCL tangent modulus, greater stifle joint stability and a lower resultant cranial tibial thrust on the CrCL than the Rottweiler specimens.

In conclusion, there is an increased chance of CrCL rupture in some Rottweilers compared to Racing Greyhounds.

CHAPTER EIGHT

GENERAL DISCUSSION AND SUMMARY

8.1 GENERAL DISCUSSION

In the introduction to this study it is stated that anecdotally, some breeds are reported to be more prone to rupture of the cranial cruciate ligament than others.
The prospective random survey and retrospective examination of Veterinary School case records have shown that the Rottweiler breed in the UK is predisposed to and has a high incidence of cranial cruciate ligament rupture. In contrast, Racing Greyhounds rarely present with this condition.
An examination of the age at onset of cranial cruciate ligament rupture in the UK dog population showed that the condition was seen at a younger age in Rottweilers than in other dogs.

Having established the incidence of cranial cruciate ligament rupture in Rottweilers and Racing Greyhounds, the conformation, kinematic gait parameters and cadaver stifle joint biomechanics of the two breeds were studied.

The study of the kinematic gait parameters of Rottweilers and Racing Greyhounds involved two complementary methods.
Firstly, the well established use of a high speed cinecamera mounted on a manually-propelled trolley and the subsequent frame by frame analysis using a computerised image analysis system of walking and trotting infront of a measured grid background.
Secondly, a microcomputer-based kinematic gait analysis system, Gaitway, which was adapted for this study from its original use in humans. This method relies on the

movement of hole-punched computer tapes passing through a reading head assembly which counts the number of holes passing through the assembly during set time intervals. Certain temporal and spatial kinematic gait parameters can be accurately calculated by the microcomputer from the data collected as the inter-hole spacing and sampling rate are known.

Part of the study of these methods and the adaption of the Gaitway system involved the examination of the ability of the Gaitway system to accurately depict the spontaneous walk and also the influence on normal gait of the physical attachment of the hole-punched computer tapes to the hindlimbs of the dogs.

This study showed that the Gaitway system does accurately reflect the spontaneous walk. The kinematic gait parameters calculated by the Gaitway system were not affected by the tape attachment to the hindlimbs. However, the angular movements of the stifle joint during the gait cycles recorded by the cinecamera were affected by the system, therefore the hindlimb angular joint movements were not measured when the Gaitway system was simultaneously attached.

Although there was no statistically significant difference between the mean standing stifle joint angles of Rottweilers and Racing Greyhounds, Rottweilers have a greater range of stifle joint movement (flexion and extension) during locomotion and they have a more extended stifle joint when the limb initially weight-bears compared to Racing Greyhounds. The Rottweilers also extend their hindlimbs further forward (protraction) than Racing Greyhounds which, together with the greater stifle joint extension, leads to a greater stride length to limb length ratio in Rottweilers.

Rottweilers also weight-bear for a longer period of the gait cycle duration than Racing Greyhounds at the trot.

In order to establish the relationship between joint angulation and failure of the cranial cruciate ligament, the biomechanical properties of the stifle joint and the osseous geometry of the tibial plateau at particular joint angles determined from the gait analysis were examined.

Using cadaver stifle joints of Rottweilers and Racing Greyhounds, the craniocaudal stability of the joints, when cyclically loaded in a direction simulating the cranial drawer test, was measured. This was followed by the loading to failure of the cranial cruciate ligament along one of two different loading axes at different joint angles to determine the structural and material properties of the Rottweiler and Racing Greyhound cranial cruciate ligaments *in vitro.* The dimensions of the cranial cruciate ligaments and the slope of the tibial plateau at the point of contact with the femoral condyle were also measured.

There was found to be up to two times greater craniocaudal laxity in Rottweiler stifle joints compared to Racing Greyhounds at the same joint angles. In both breeds the craniocaudal laxity of the stifle joints increased as the joint flexed.

The structural and material properties measured included the ultimate load to failure and linear stiffness of the femur-CrCL-tibia complex and the tensile strength of the cranial cruciate ligament.

The tensile strength of the Racing Greyhound cranial cruciate ligament was greater than that of the Rottweiler when the ligament was cranially loaded to failure in extension.

The mean ultimate load at failure, linear stiffness and the tensile strength of the Rottweiler specimens increased with increasing joint flexion. These properties were virtually unaffected by the joint angle in the Racing Greyhound with the mean linear stiffness decreasing with increasing joint angulation.

A cranial tibial thrust force acts to move the tibia cranially relative to the femur during weight-bearing. This force is antagonised, in part, by the cranial cruciate ligament. It has previously been reported that the magnitude of the cranial tibial thrust force is determined, in part, by the angle of the tibial plateau and the more variation in that angle, the more variation there will be in the cranial tibial thrust. The angle of inclination of the tibial plateau at the point of contact of the femoral condyles and the tibial plateau, which moves as the joint flexes and extends, was measured.

In both Rottweilers and Racing Greyhounds, as the joint moved from extension to flexion, the inclination of the tibial plateau became more positive, ie. a downward slope. The range of the tibial plateau contact angles between extension and flexion and the symmetry between the medial and lateral sides of the tibial plateau were greater in the Rottweiler than the Racing Greyhound. Both of these factors would lead to a greater cranial tibial thrust being generated in the Rottweiler stifle joint resulting in a greater strain in the cranial cruciate ligament compared to the Racing

Greyhound. The differences in the tibial plateau contact angles recorded in this study could have a profound effect on the magnitude of the load acting on the cranial cruciate ligament at different degrees of joint flexion because the force acting antagonistically to the cranial cruciate ligament is crucially dependent on the tibial plateau angle.

From the results obtained, it appears that the strain on the ligament during weight bearing would be significantly reduced if the geometry of the tibial plateau changed so that it sloped downwards to a lesser degree.

To combine and summarise the findings of the kinematic gait analysis and the biomechanical testing of Rottweilers and Racing Greyhounds;

One function of the cranial cruciate ligament is to prevent hyperextension of the stifle joint. Greater extension of the stifle joint, greater advancement of the foot at foot placement and greater craniocaudal stifle joint laxity in the Rottweiler compared to the Racing Greyhound lead to a greater tendency for the stifle joint to hyperextend. This will be limited, in part, by the cranial cruciate ligament resulting in a greater strain on the ligament.

The Rottweiler cranial cruciate ligament is weaker than that in the Racing Greyhound at all flexion angles tested and its strength decreases as the stifle joint extends. The normal Rottweiler stifle joint is more extended than that in the Racing Greyhound during locomotion, especially at foot placement, when the cranial cruciate ligament is weaker. As the joint flexes, the ligament is stronger but the greater downward slope of the tibial plateau contact point results in a greater force tending to move the tibia forward relative to the femur which must be counteracted by the cranial cruciate ligament. Therefore it appears that as the Rottweiler stifle joint flexes from full extension, the ligament and its attachments become biomechanically stronger but the load on the cranial cruciate ligament becomes greater.

From the results of both the kinematic gait analysis and the biomechanical testing, it can be concluded that there is an increased risk of cranial cruciate ligament rupture in some Rottweilers compared to Racing Greyhounds. The high incidence of cranial cruciate ligament rupture in the Rottweiler breed has been shown by the survey and examination of case records.

The conformation and gait of the Rottweiler hind limbs do appear to influence cranial cruciate ligament damage. The amount of stifle joint extension at foot placement, the greater stride to limb length ratio, the greater joint laxity allowing greater stifle extension and the greater downward slope of the tibial plateau in flexion, all tend towards a greater strain on the cranial cruciate ligament which this study has shown to be weaker in extension than flexion.

8.2 FUTURE WORK

This section outlines some suggestions from the author as to further work, development and scientific investigations which could follow on from this study.

The variable breed incidence of cranial cruciate ligament rupture in the general dog population has been demonstrated. Therefore although further work should involve the continuation of the study of cranial cruciate ligament rupture in Rottweilers and Racing Greyhounds, the investigation of other breeds should also be proposed. Examples of possible additional breeds to study are the German Shepherd Dog which this study has shown to have a lower than expected incidence of cranial cruciate ligament rupture and the Labrador which has a level of incidence expected from the popularity of the breed.

The kinematic gait analysis data collected in this study could be further advanced by looking at the amount of rotation of the tibia relative to the femur during locomotion. The hypothesis that the tibia rotates relative to the femur to the same extent in the Rottweiler as in the Racing Greyhound during the normal gait cycle could be tested. A further kinematic study would be to examine, in a greater number of breeds, the statement that the stride length of a dog is proportional to its hindlimb length at different speeds of locomotion.

Further examination of other breeds of dog to compare the range of motion of the stifle joint during locomotion, especially at foot placement, between breeds to see if there is a correlation between the straightness of the stifle at foot placement and the breed incidence of cranial cruciate ligament rupture.

No kinetic gait analysis studies were carried out in this project but to do so in the Rottweiler and Racing Greyhound would complement the work carried out so far. Force plates and strain gauges may be used together with kinematic techniques to determine how the forces acting on the stifle joint generally and on the cranial cruciate ligament specifically change throughout the weight-bearing phase of the gait cycle in different breeds.

The biomechanical studies of the Rottweiler and Racing Greyhound stifle joints have provided some useful data, especially relating to stifle joint stability and the osseous geometry of the tibial plateau. These factors should be investigated further both for these and for other breeds.

Suggested hypotheses to be tested are;

The femorotibial contact angle influences the amount of stress on the canine cranial cruciate ligament during weight-bearing.

The femorotibial contact angle of the canine stifle joint can be accurately determined at different joint angles *in vivo* using non-invasive imaging techniques.

There is no significant difference in the symmetry between the medial and lateral tibial plateau angles in different breeds of dog.

The degree of rotation of the tibia relative to the femur influences the craniocaudal stability of the joint and the tensile strength of the cranial cruciate ligament of Rottweiler and Racing Greyhound cadaver stifle joints at different angles of joint flexion.

In this study no histological examination was carried out on the cranial cruciate ligaments, either intact or following the loading to failure.

Histological examination of the ligaments would determine if there is any morphological difference in the cranial cruciate ligament between different breeds of dog or at the point of rupture of the ligament compared to an intact ligament.

As expected at the end of most scientific studies, it is found that although some questions will be answered by the work, there will always be more questions to answer and different avenues to follow. The author has detailed some suggested further work arising from this study and some scientific hypotheses which may be tested.

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Canine kinematic hindleg gait analysis using a microcomputer

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ABSTRACT

A microcomputer-based gait measurement system, originally developed for human subjects, has been adapted for analysis of canine walking and trotting gaits. Examples of gait in a normal and an abnormal dobermann are shown to demonstrate the collection and presentation of kinematic data of locomotion. The potential of the system for clinical and research work is discussed.

INTRODUCTION

Gait analysis of many species occurs daily in veterinary practice. The gait of animals is visually assessed as an aid to diagnosis and to monitor the progression of disease. Although these observations are of major importance, they are subjective, qualitative assessments and therefore imprecise. An accurate, inexpensive, easy to use, objective and quantitative gait measurement system could be of great value to a clinician or researcher wishing to monitor the progression of a disease condition, to compare different treatment regimens or to analyse the gaits of normal animals.

The first recorded quantitative gait analysis work was cited by Marey in 1874 using a pneumatic recording device. Since then researchers have used various gait analysis techniques. Gait analysis is divided into two distinct disciplines: kinetic and kinematic analysis.

Kinetic analysis studies changes of motion and includes the effect on the subject. Devices used for canine kinetic gait analysis comprise: force plates (Jayes and Alexander 1978, Budsberg and others 1987, 1988, O'Connor and others 1989, McLaughlin and others 1991), strain gauges (Rubin and Lanyon 1982, Bouvier and Hylander 1984) and the Kaegi analysis system (equine: Auer and Butler 1985).

Kinematic analysis studies motion without taking into account the forces acting on the subject and provides measurements of the temporal and spatial parameters of the gait. Kinematic measurements are adequate for these canine studies and equipment for kinetic measurements will not be considered further in this paper. Devices which have been used previously for this purpose include: electrogoniometers (canine: Adrian and others 1966, Kinzel and others 1976), high speed cinematography (canine: Tokuriki 1973, Wentink 1976, 1977, Charteris and others 1979, Goslow and others 1981) and automatic motion analysis systems (equine: Atha 1984).

Brief summaries of these techniques and more complex systems used for equine research have been reviewed by Fackleman and Seeherman (1982), Dalin and Jeffcott (1985) and Leach (1987).

The equipment available for kinematic gait measurement has certain disadvantages; the cost of the apparatus, the delay in analysing the recorded data, and the need for technical operating staff. A new method of quantitative canine gait analysis is the subject of this paper. A microcomputer based kinematic gait analysis system, 'Gaitway', was developed for use in humans by Law (1987). It provides accurate, rapidly available kinematic data in a simple manner and is ideal for the clinical and research work for which it is currently being used in human subjects. The Gaitway system has been adapted to accommodate canine walking and trotting gaits. An important feature of the adapted Gaitway is that data from both hindlegs are collected simultaneously allowing for a direct comparison of the left and right hindleg gait parameters recorded during the same period of locomotion.

MATERIALS AND METHODS

This work was carried out using clinically normal dogs and clinical cases presented to the Small Animal Clinic, Royal (Dick) School of Veterinary Studies, Edinburgh. It involved the measurement and analysis of only hindlimb kinematic gait parameters; forelimb movement was not recorded.

The original Gaitway system (Law 1987) makes use of two hole-punched computer tapes which are attached to the feet of the subject by adhesive tape. The holes are accurately spaced at intervals of $^1/_{10}$th inch. These tapes run though an optical reading head which contains a local counter, linked to a microcomputer via an eight-bit parallel cable. The optical reading head registers the holes in the tape moving through as the subject walks and the number of holes is counted and stored by a local counter. The microcomputer records the local counter reading at a rate of 256 times per second, ie, the number of holes which have passed through the reading head, or the total tape movement up to this time. Because the inter-hole spacing and the sampling rate are known, the microcomputer accurately calculates the required temporal and spatial kinematic data. A display in either tabular form on a visual display unit (VDU) or on hard copy is provided for all the gait cycles recorded, the stride lengths, swing phase durations and double support times, the average walking speed (m/s) and the cadence (steps/min). Finally, it plots the foot velocity during the swing phase versus time for each foot and each gait cycle (points are plotted every 1/24s).

Application to measurement of canine gait

Because the microcomputer has only one parallel input/output port, the counts arising from the movements of the left and right tapes are combined in the local counter so that it is the sum of the two movements which is stored in the microcomputer memory. This is acceptable in the measurement of human walking as there are always two periods in each gait cycle when the two feet are simultaneously stationary in contact with the floor and by detecting these 'double support' periods appropriate algorithms in the computer program can be used to note the transfer of movement from one limb to the other. If the subject is instructed to 'start with the right foot' the data can be correctly assigned to the left and right limbs.

The extension of the system for use from humans to canine subjects involves several problems. First, a dog cannot be relied upon to start the walk with a particular foot so that some independent umambiguous method of assigning the tape movements to each limb is needed, secondly, in quadrupedal gait there may be no double support periods in, say, the movements of the hindlimb pair, as both may be out of contact with the floor and in movement at the same time. (In humans, too, the double support period becomes progressively shorter as the walking velocity increases and becomes zero at the transition between walking and running.) Finally, dogs do not tolerate adhesive tape attached to the digits or pads; nor will they tolerate any type of shoe to which the hole-punched tapes may be attached.

The last difficulty is solved by using a length of monofilament nylon line tied around the hindlegs, just proximal to the metatarsophalangeal joint to which the computer tapes are attached. It is well tolerated by the dogs and results in firm fixation of the tapes. The minimal drag of the computer tapes passing through the reading head, coupled with the hindleg tape attachments, does not significantly affect the temporal and spatial parameters measured by the Gaitway system when compared to free locomotion (C. Wingfield, unpublished data). Dogs require a period of familiarisation to the tape attachments, reading head drag and minor noise of the Gaitway system by having some practice walks with the tapes attached. The majority require only four to six walks to become accustomed to the system. Of 52 dogs, of various breeds, which have been walked attached to the system, only four (7·7 per cent) failed to tolerate the tapes.

Adaption of the Gaitway system to circumvent the first two difficulties has resulted in two electronically independent systems, one for each hindfoot. The hole-punched tapes from each hindfoot pass through a container housing two independent optical reading heads and two independent local counters. The left side tape, reading head and local counter are coupled to one microcomputer, the right side to a separate but identical microcomputer, each with a VDU (Fig 1). The original program is used in each computer during data collection. Although both hindfeet are recorded during the same walk, to allow comparison between left and right hindfeet gaits and the interlacing of the foot velocity versus time

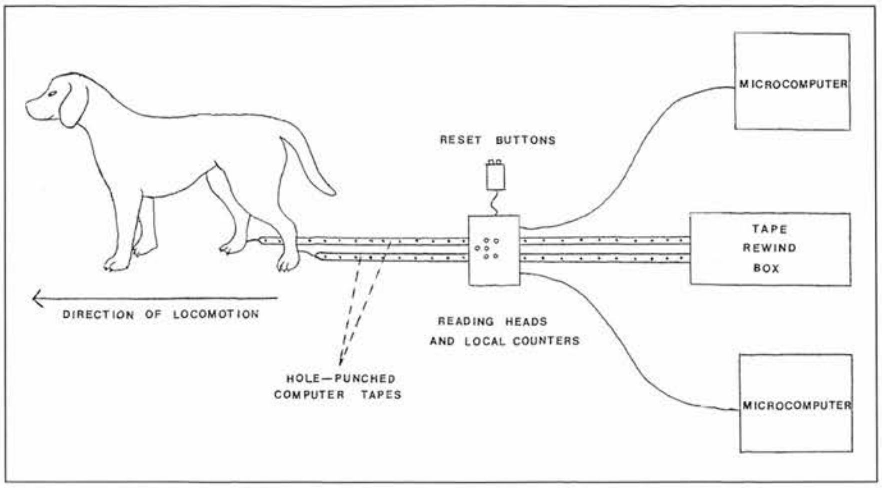

FIG 1. Schematic diagram of the adapted Gaitway system

plots, both sides must start recording data simultaneously whichever foot moves first. The electronic circuits include two bistables (flip-flops). These are 'set' by means of two push buttons immediately before the test walk is to begin and both are 'reset' by the first detected movement of either tape, which instructs both microcomputers to begin data collection. The time base of the two records is thus accurately synchronised and they may later be combined into a single display along a common axis. The recorded data is presented in the same format on a VDU as the original Gaitway system but all the data shown on one VDU will have come entirely from the left or right foot.

An extra program is used following data collection to print or display the interlaced foot velocity versus time plots for alternate left and right swing phases for the entire walk so that left and right foot parameters are seen sequentially and in a correct temporal relationship (Figs 3, 4, 5 and 6). Thus the adapted Gaitway system does not rely on the detection of a double support time of the hindfeet to function, so it can also analyse the trotting gait where there is no period in the gait cycle when both hindfeet are simultaneously stationary on the ground.

The gait parameters used throughout this study are defined as: Gait cycle duration, the time

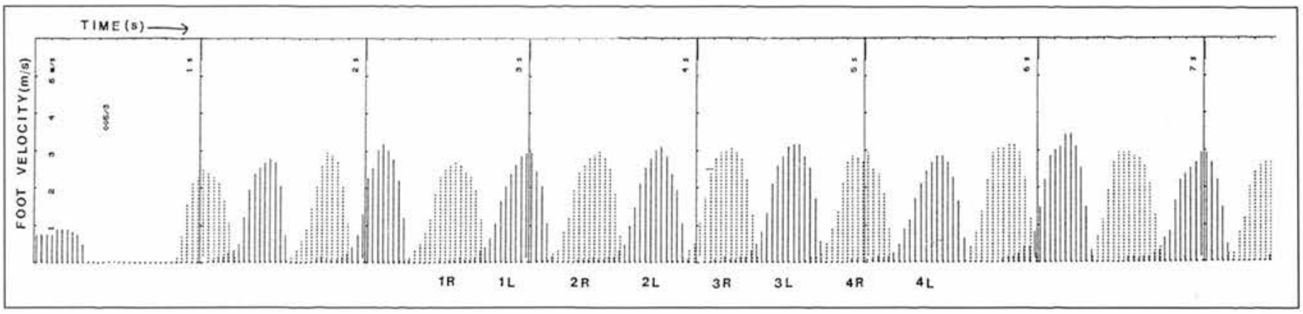

FIG 3. Case 1. Normal dobermann. Foot velocity (m/s) plotted against time (seconds) for each consecutive hindleg stride during the walk. ——— Left hindfoot, - - - - - Right hindfoot. Gait cycles numbered 1 to 4 correlate with those represented in Table 1

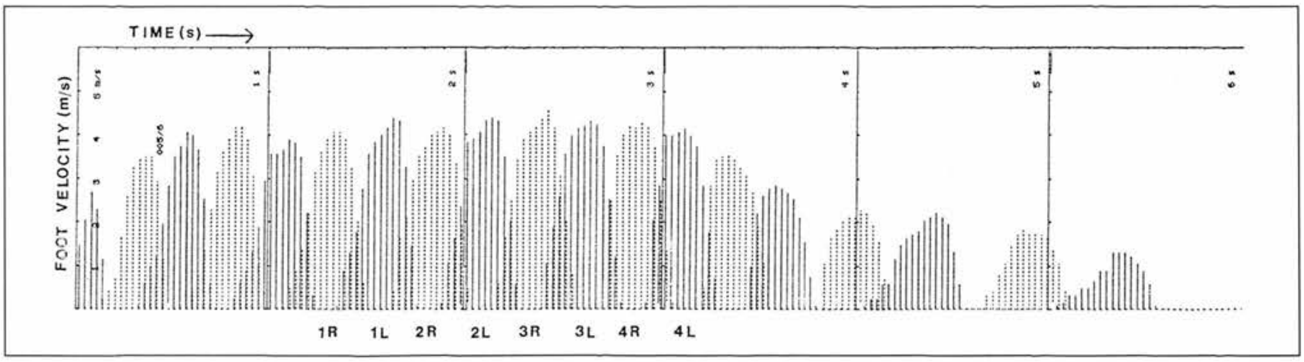

FIG 4. Case 1. Normal dobermann. Foot velocity (m/s) plotted against time (seconds) for each consecutive hindleg stride during the trot. ——— Left hindfoot, - - - - - Right hindfoot. Gait cycles numbered 1 to 4 correlate with those represented in Table 1

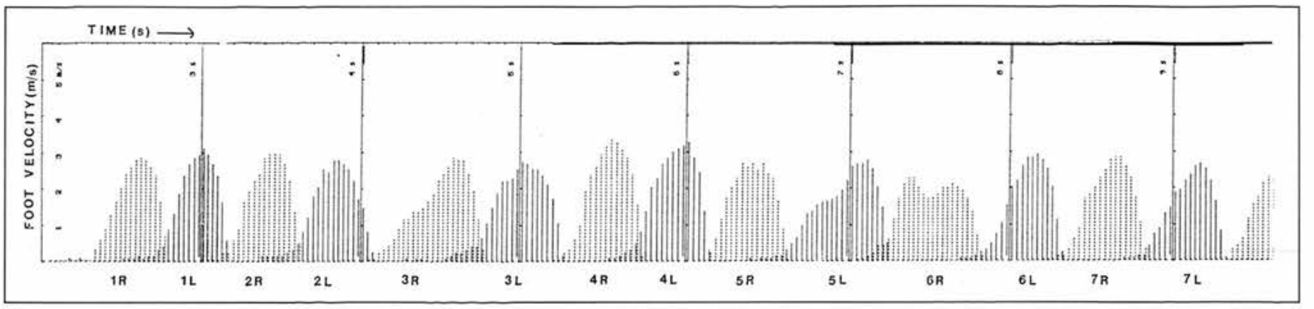

FIG 5. Case 2. Abnormal dobermann. Foot velocity (m/s) plotted against time (seconds) for each consecutive hindleg stride during the walk. ——— Left hindfoot, – – – – – Right hindfoot. Gait cycles numbered 1 to 7 correlate with those represented in Table 1. In this plot only, the start of the walk has not been shown. (See horizontal time axis)

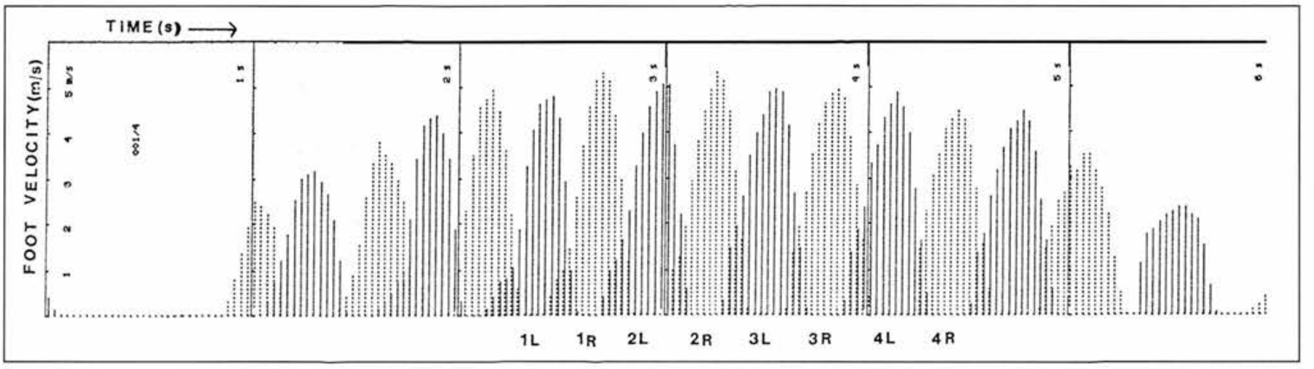

FIG 6. Case 2. Abnormal dobermann. Foot velocity (m/s) plotted against time (seconds) for each consecutive hindleg stride during the trot. ——— Left hindfoot, – – – – – Right hindfoot. Gait cycles numbered 1 to 4 correlate with those represented in Table 1

which elapses between successive impacts of the same foot on the ground; stride length, the distance the foot moves during one gait cycle relative to the ground; stance phase duration, the time during the gait cycle when the foot is at zero velocity on the ground; swing phase duration, the time during the gait cycle when the foot is moving relative to the ground; and hindlimb double support time, the time during the gait cycle when both hindfeet are on the ground simultaneously.

During a normal gait there is some variation of parameters between each gait cycle. Therefore, a minimum number of three consecutive gait cycles per walk is required for a meaningful analysis of that gait (Hildebrand 1968, Fredricson and others 1972, Drevemo and others 1980). The analysed gait cycles should be from mid-walk when the subject has settled into its usual, even if abnormal, gait pattern.

RESULTS

The adapted Gaitway system has been used on various breeds of dog with normal and abnormal gaits. The following are examples of two dogs recorded at the walk and trot; one is clinically normal, the other has a neurological deficit.

Fig 2 is a schematic diagram of the foot velocity versus time plot for one foot showing the swing and stance phases and the maximum foot velocity for two gait cycles. The extra software program interlaces this plot and a similar one

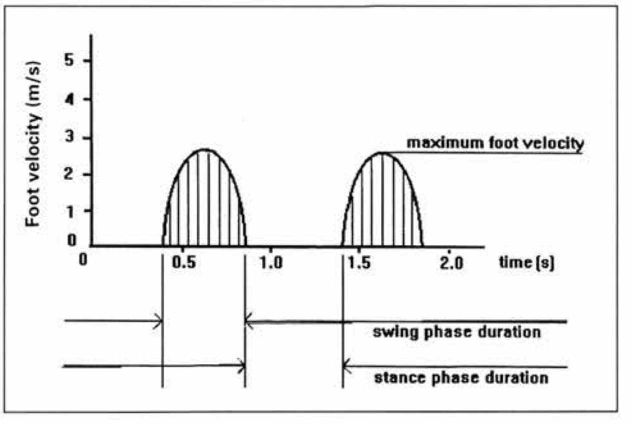

FIG 2. Schematic diagram of a foot velocity versus time plot, for one foot only, showing the swing phase duration, stance phase duration (zero foot velocity) and maximum foot velocity for two gait cycles

recorded simultaneously for the other foot, the combined plot compares the temporal movement of both feet as shown in Figs 3 to 6.

Case 1

Case 1, a 3·5 year old dobermann bitch, is clinically normal with no history of orthopaedic or neurological disease.

Table 1 shows the mean (± standard deviation [SD]) of the temporal parameters of four consecutive gait cycles measured with the adapted Gaitway system for the dobermann at walk (speed 1·02 m/s) and trot (speed 2·11 m/s). Figs 3 and 4 show the computer generated foot velocity versus

Table 1. Mean (± SD) stance and swing phase durations of consecutive gait cycles, left and right hindlegs, measured at walk and trot for a dog with normal gait (case 1) and abnormal gait (case 2)

	Stance phase duration (s)		Swing phase duration (s)	
	Left	Right	Left	Right
Case 1 (normal)				
Walk (n=4)	0·366 (0·032)	0·366 (0·027)	0·465 (0·019)	0·445 (0·021)
Trot (n=4)	0·142 (0·004)	0·144 (0·009)	0·367 (0·019)	0·302 (0·009)
Case 2 (abnormal)				
Walk (n=7)	0·427 (0·096)	0·453 (0·055)	0·578 (0·086)	0·544 (0·099)
Trot (n=4)	0·184 (0·033)	0·186 (0·039)	0·410 (0·008)	0·390 (0·014)

n Number of consecutive gait cycles measured

time plots, walk and trot, respectively, which are obtained by interlacing the data from the independently recorded left and right feet. The regularity and repeatability of the temporal parameters of each gait cycle, at walk and trot, is readily visible from the plots. Quantitatively, Table 1 shows the variation of individual parameters about the mean, shown by the SD, are small at both the walk and trot.

Case 2

Case 2, a 7·5 year old dobermann dog, has bilateral hindlimb ataxia with proprioceptive defect. Diagnosis, confirmed by myelography, is cervical spondylomyelopathy ('Wobbler' syndrome).

Table 1 shows the mean (± SD) of the temporal parameters for seven consecutive gait cycles at walk (speed 0·98 m/s) and four consecutive gait cycles at trot (speed 2·04 m/s) for the ataxic dobermann. Figs 5 and 6 show the foot velocity versus time plots for the walk and trot. The plot for the walk shows the marked variation of the swing and stance phase periods between each gait cycle both in the duration of the phase and the maximum foot velocity on the left and right sides. The plot for the trot (Fig 6) shows the return of the regularity and repeatability of each gait cycle. Quantitatively, Table 1 shows that the means of the individual values for the left and right sides do vary as seen for the normal dobermann. However, for the ataxic dobermann at the walk, there is much greater deviation of the individual values about the mean for both the swing and stance phase durations. The variation about the mean of individual values of the stance phase duration at trot in the abnormal dobermann are not significantly changed from the variation seen at walk, however, the variation about the mean of individual values of the swing phase duration at trot compared to walk are greatly reduced and are similar to the normal dobermann.

DISCUSSION

The two cases described illustrate the ability of the adapted Gaitway system to provide a permanent record of the gait of the dog, walking and trotting. The quantitative kinematic data are rapidly available from a system which is non-invasive, pain-free, easy to use and mobile. The temporal data are accurate to 1 ms and the spatial to 1/10th inch. The data collected show clearly any differences in the trajectories of the left and right hindfeet. Moreover, these differences can be used to monitor later changes and response to therapy. The ability of the system to compare the left and right hindfeet during the same gait is crucial when analysing abnormal gaits.

The two cases also demonstrate the system's ability to compare a normal canine gait, either at walk or trot, with an abnormal gait both visually and quantitatively. This is important when assessing if the trajectory of the hindfoot during the swing phase is affected by the disease condition (Fig 5) or whether the swing phase is 'smooth' but the duration is shortened or extended. The example of the ataxic dobermann (case 2) clearly shows the improvement of gait when it moves from a walking to trotting gait pattern. The variation of the swing phase duration between individual gait cycles in the abnormal dobermann at walk is great, but that variation becomes much less when the gait changes to trot. This is probably due to the increased momentum of the hindlegs, at the greater trotting speed, resulting in less reliance on fine neuromuscular coordination for a normal gait pattern.

The system will show when there are only small variations between individual gait parameter values of one side, either left or right hindlimb, but there are a significant differences between the mean values of both sides. This applies to the swing and stance phase durations and the maximum foot velocity values. This is seen in dogs with a unilateral hindlimb lameness where the stance phase duration of the painful leg is shortened and the contralateral hindlimb has a shortened swing phase duration and a greater maximum foot velocity. A permanent, quantitative record of the hindlimb lameness is thus available.

The basic data produced by the adapted Gaitway system can be used to determine other parameters such as total gait cycle duration, the swing to stance phase duration ratio which differs from the normal in the pathological gait (Adrian and others 1966) and the duty factor (the stance phase duration as a fraction of the total gait cycle duration). The assessments of the adapted Gaitway system for canine gait analysis are still in their early stages and many more dogs, especially those with abnormal gaits, must be recorded before its full potential can be realised.

This study did not measure any forelimb gait parameters. However, with modification to the method of tape attachment, to divert the tapes around the hindlimbs, the authors believe that the measurement and analysis of forelimb movement using the Gaitway system could also be very useful.

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ABSTRACT

Keratitis sicca and diabetes mellitus in a dog

A NINE-year-old poodle bitch had increasingly worsening epiphora, for which no cause could be found. Six months later the animal suffered progressive weight loss, loss of vision and had polydipsia/polyuria. The eyes produced abundant mucopurulent exudate, had blepharospasm and the corneas were rough and dull. Schirmer values were markedly reduced. Urinalysis revealed glycosuria, ketourea and proteinurea. Serum glucose was also raised. Diabetes mellitus with concurrent keratitis sicca was diagnosed. Crystalline protamine porcine insulin was prescribed. The keratitis sicca was treated with a collyrium containing neomycin sulphate, polymixin B and dexamethasone. Artificial tears were also administered. Treatment for the keratitis sicca was stopped after nine days when Schirmer tests were normal. No relapse occurred. Insulin dosage was stabilised after nine days. As the factors predisposing to keratitis sicca were not present, it is suggested that keratitis sicca and diabetes mellitis were linked in this case because the eye lesions resolved when the diabetes was controlled.

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